

SOME PATENTS OF INVENTOR Bibhas R. De

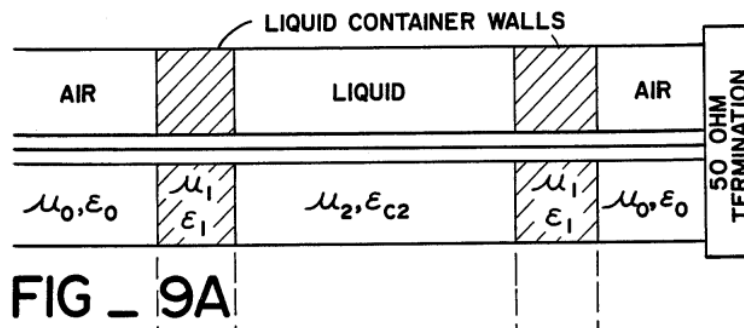
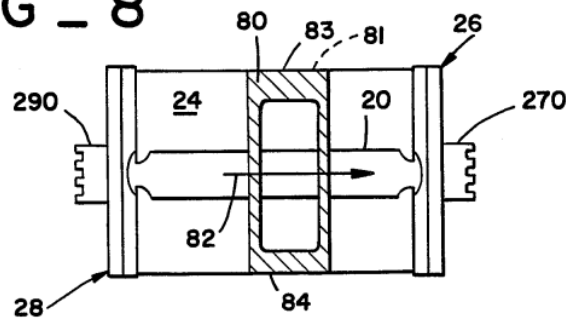
U.S. Patent

Sep. 12, 1989

Sheet 5 of 6

4,866,371

FIG - 8



[54] SAMPLE ACCOMMODATOR AND METHOD FOR THE MEASUREMENT OF DIELECTRIC PROPERTIES

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[73] Assignee: Chevron Research Company, San Francisco, Calif.

[21] Appl. No.: 252,023

[22] Filed: Sep. 28, 1988

Related U.S. Application Data

[63] Continuation of Ser. No. 907,763, Sep. 15, 1986, abandoned, which is a continuation of Ser. No. 637,376, Aug. 2, 1984, abandoned.

[51] Int. Cl.⁴ G01R 27/04

[52] U.S. Cl. 324/58.5 R; 324/58.5 A; 324/58.5 B; 324/347

[58] Field of Search 324/347, 58 A, 58 B, 324/58 C, 58 R, 58.5 A, 58.5 B, 58.5 C, 58.5 R

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Primary Examiner—Reinhard J. Eisenzopf

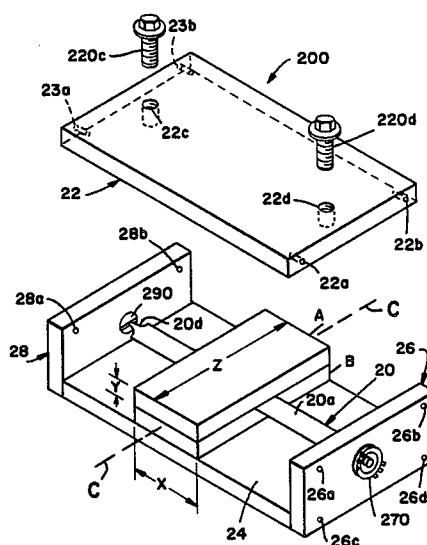
Assistant Examiner—Jose M. Solis

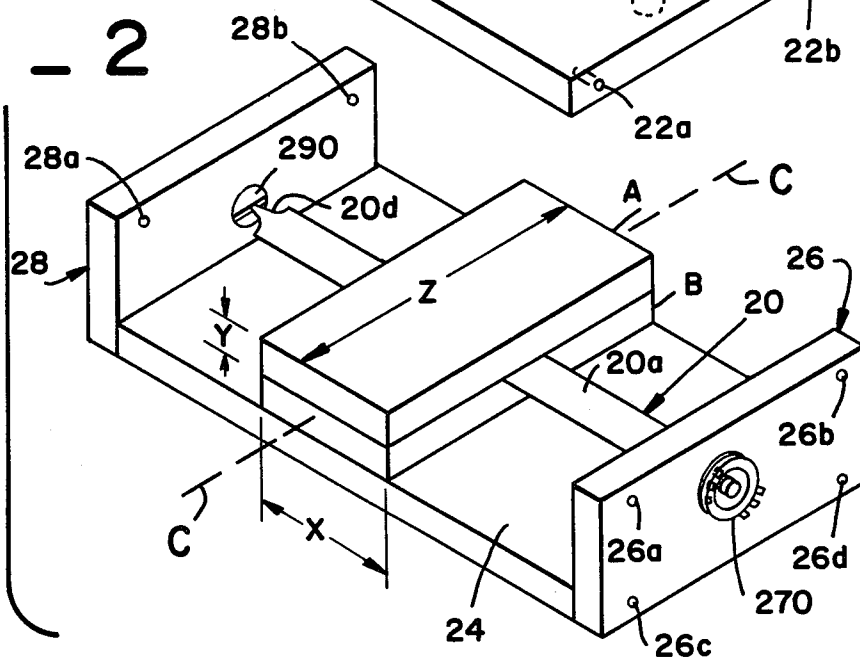
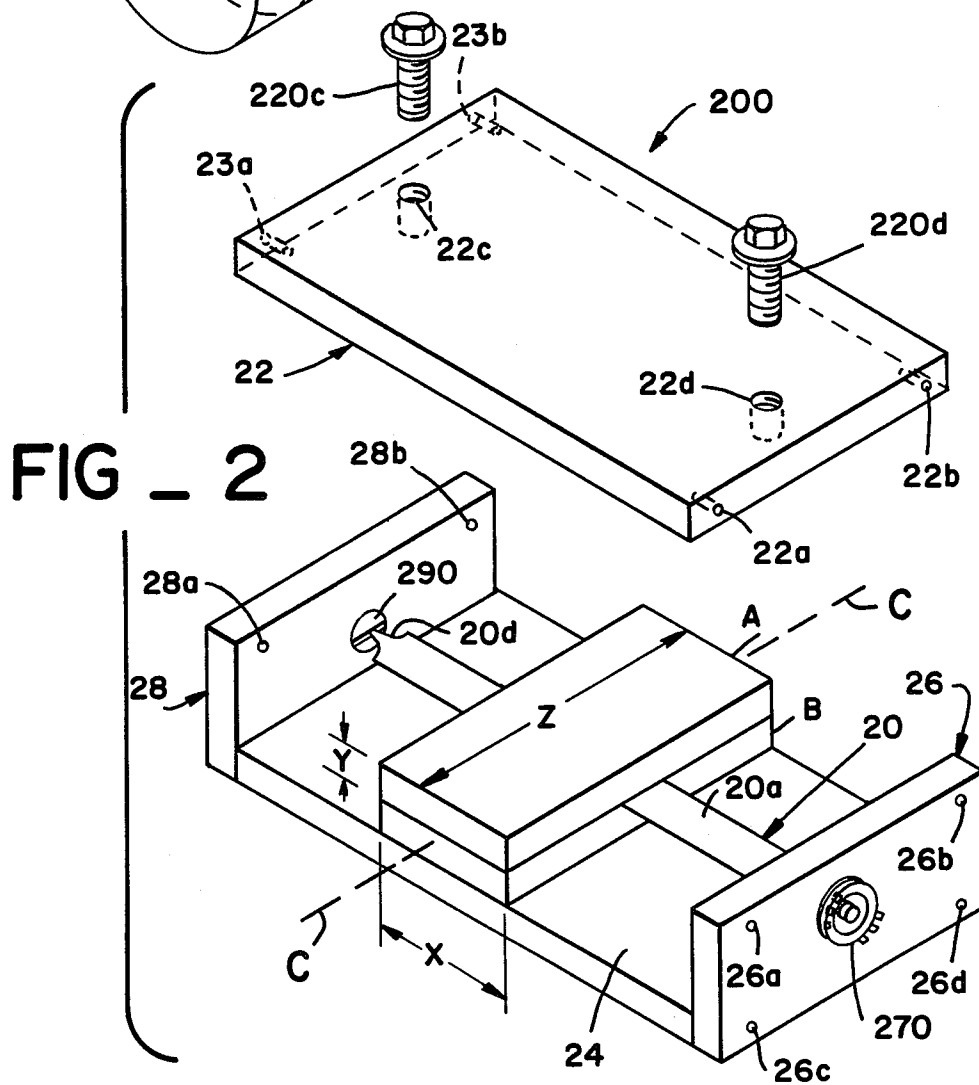
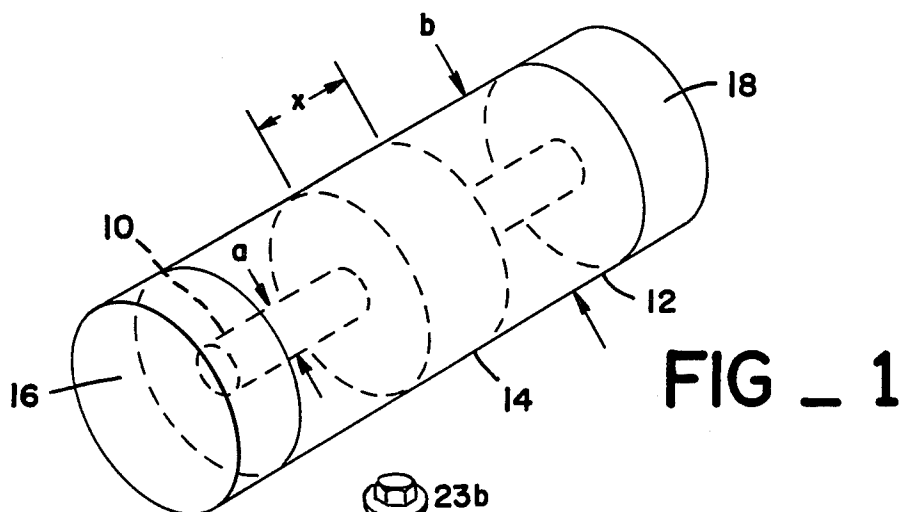
Attorney, Agent, or Firm—E. J. Keeling; E. A. Schaal

[57] ABSTRACT

A sample accommodator for the measurement of dielectric properties includes a conductive strip having two planar surfaces, and two ground planes, one parallel to each of the planar surfaces of the conductive strip. At each end, the strip passes through but is electrically isolated from an endplate which is electrically and physically connected to each ground plane and which maintains the relative positions of the ground planes. Dielectric properties are measured by placing a sample between each face of the strip and the ground plane parallel to it.

13 Claims, 6 Drawing Sheets





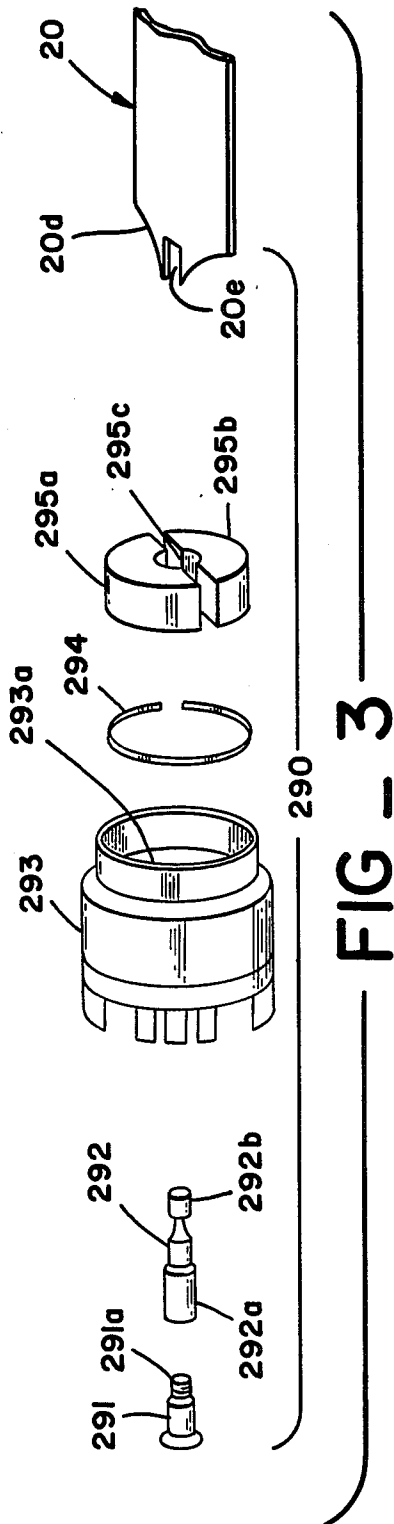


FIG - 3

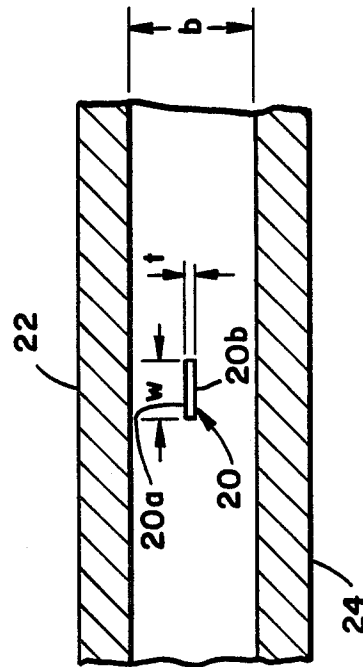


FIG - 5

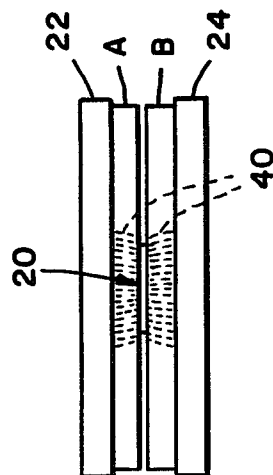


FIG - 4

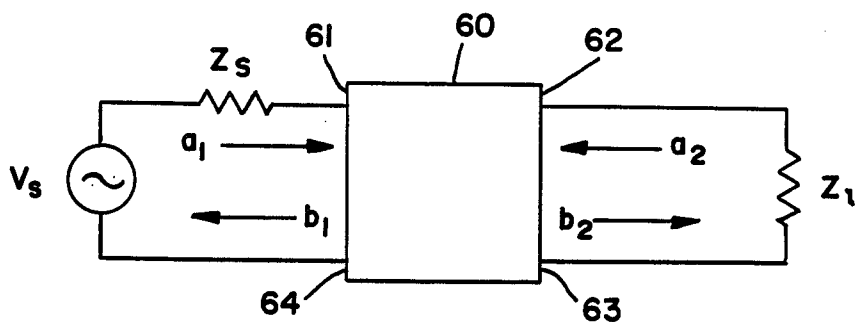


FIG _ 6

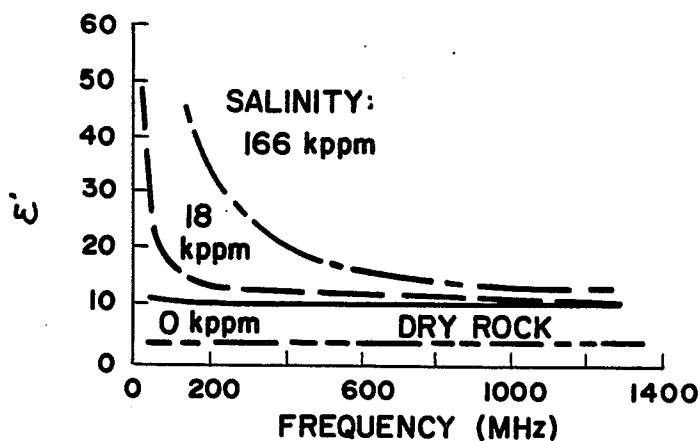


FIG _ 10A

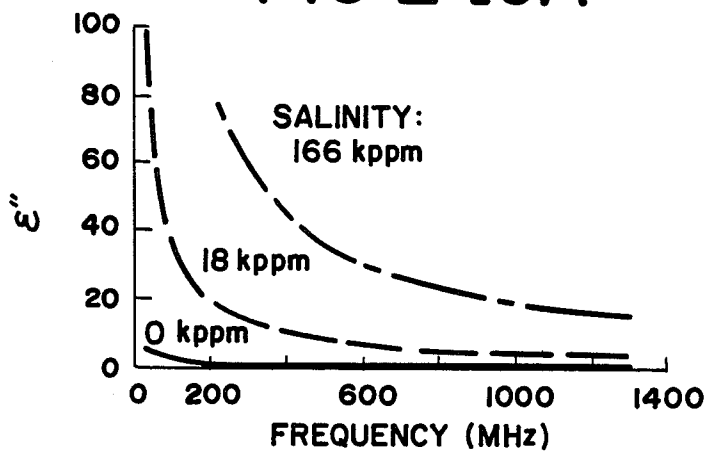


FIG _ 10B

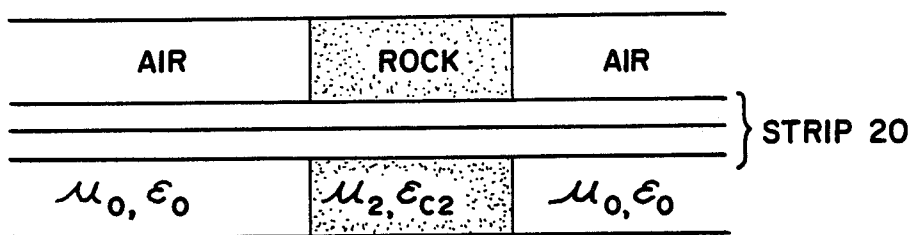


FIG _ 7A

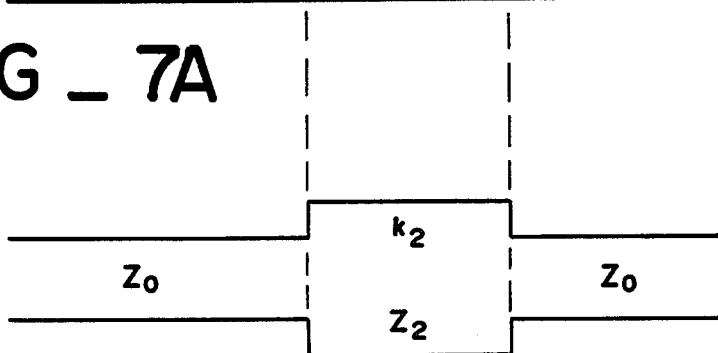


FIG _ 7B

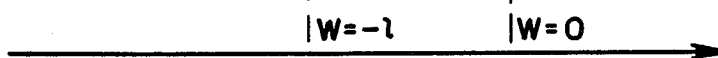


FIG _ 7C

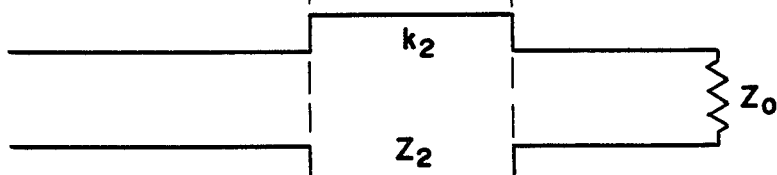


FIG _ 7D

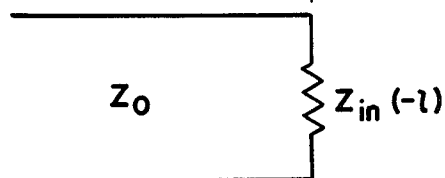


FIG - 8

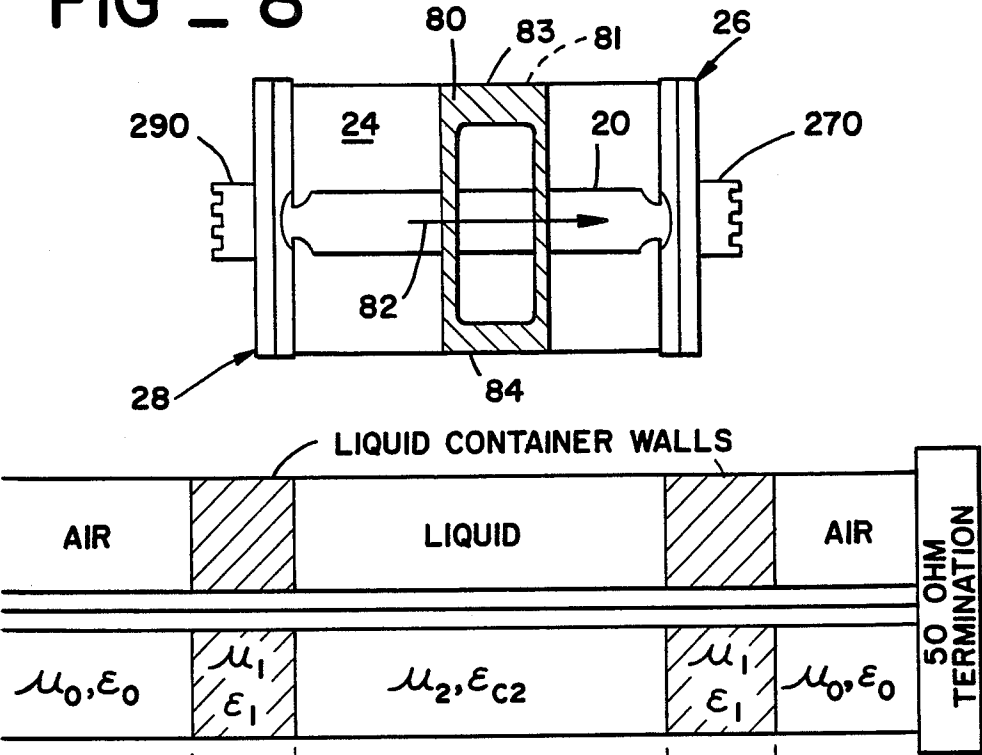


FIG - 9A

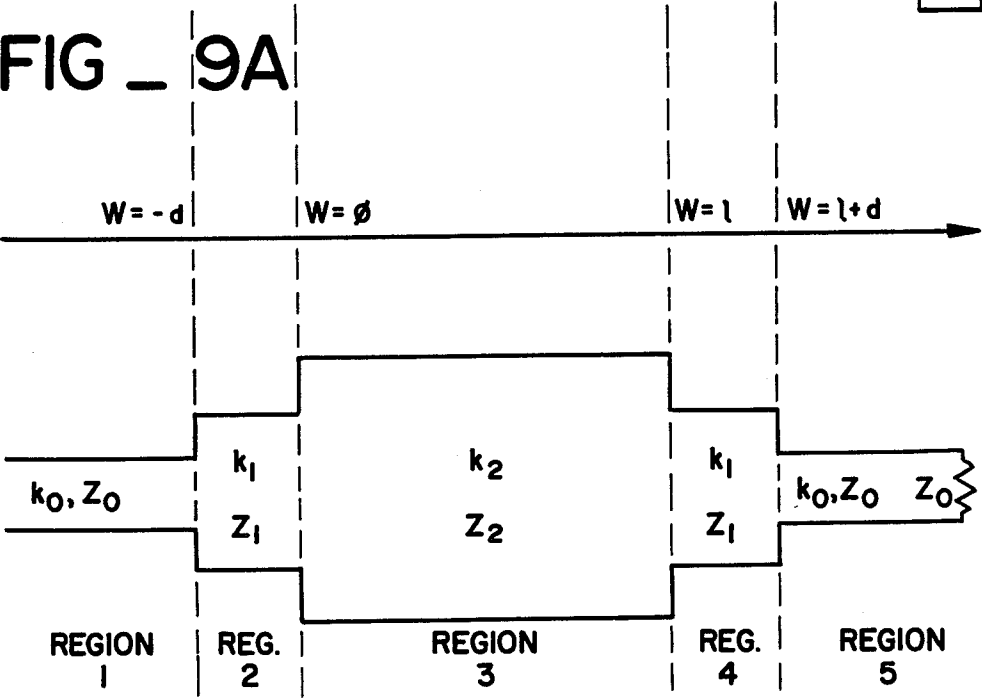
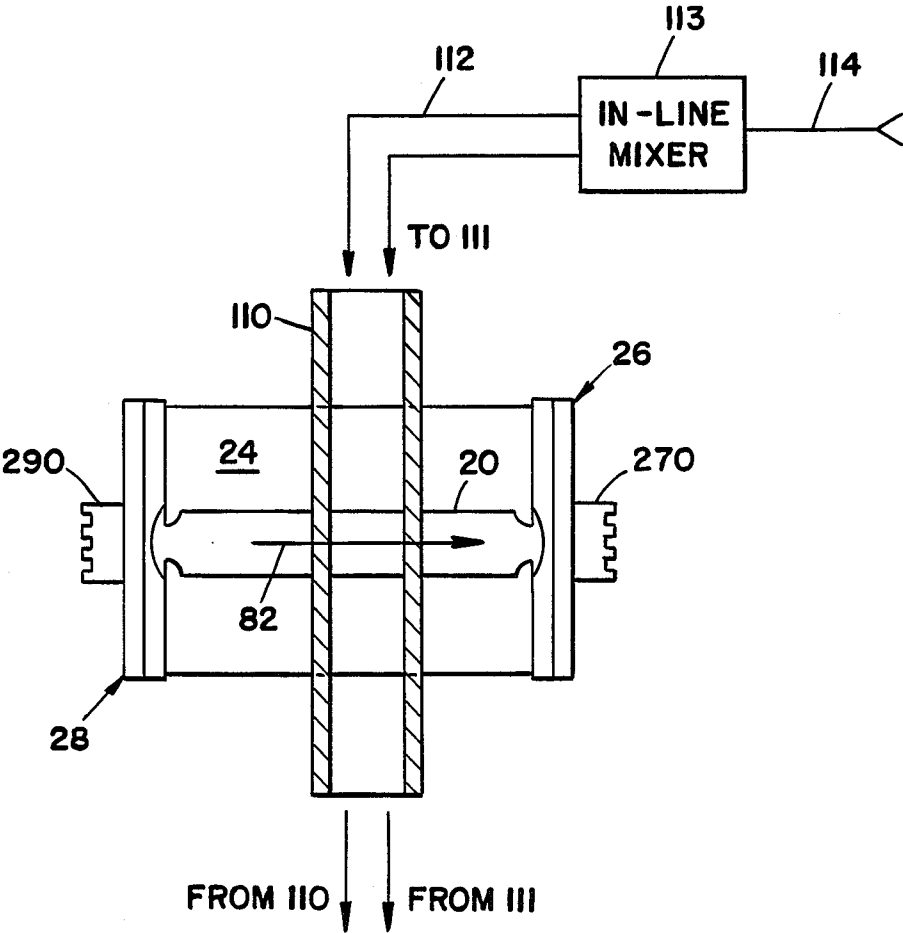


FIG - 9B



FIG_11

SAMPLE ACCOMMODATOR AND METHOD FOR THE MEASUREMENT OF DIELECTRIC PROPERTIES

This application is a continuation of application Ser. No. 907,763, filed Sept. 15, 1986, abandoned, which application is, in turn, a continuation of application Ser. No. 637,376, filed Aug. 2, 1984 and now abandoned.

BACKGROUND OF THE INVENTION

The present invention relates in general to methods and apparatus for the measurement of dielectric properties and in particular to methods and apparatus for the measurement of dielectric properties of core samples encountered in petroleum exploration.

The recent advent of a dielectric well logging technique in petroleum exploration has necessitated laboratory measurement of the dielectric permittivity of core samples in the same way that resistivity and induction logging techniques necessitated laboratory measurement of the conductivity of core samples. Known techniques of laboratory dielectric permittivity measurements in the VHF (30-300 MHz) and the UHF (300-1000 MHz) ranges (roughly covering the 20-1100 MHz range of frequencies of interest in dielectric well logging) require solid samples to be precision-machined to fit sample accommodators having precise dimensions. However, many types of core samples do not readily lend themselves to such machining.

SUMMARY OF THE INVENTION

Accordingly, apparatus according to the present invention involves a sample accommodator (i.e. a holder for the sample) for the measurement of dielectric properties. The accommodator comprises two ground planes, each of which is positioned opposite to and parallel with a different one of two surfaces of a conductive strip.

A method of measuring dielectric properties according to the present invention includes placing each of two sample portions between a different planar surface of a conductive strip and one of two ground planes. The scattering parameters of the sample portions are then measured either in the frequency domain or in the time domain. These parameters are then used to compute the real and imaginary parts of the complex dielectric constant, which represent the dielectric constant and the resistivity (or conductivity) of the sample, over a broad range of frequencies.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a prior art sample accommodator shown partially in phantom;

FIG. 2 is an exploded view of a sample accommodator according to the present invention;

FIG. 3 is an exploded view of a transition for connection of a coaxial cable to a center strip according to the present invention;

FIG. 4 is a cross-sectional view along line C of FIG. 2 through a sample accommodator containing a sample according to the present invention;

FIG. 5 is a cross-sectional view along line C of FIG. 2 through an empty sample accommodator according to the present invention;

FIG. 6 is a two-port network diagram of the sample accommodator of FIG. 2;

FIGS. 7A-7D show a schematic, transmission line representation of the sample accommodator of FIG. 2;

FIG. 8 is a view in top plan of a sample accommodator having compartments for liquid sample containment according to the present invention;

FIGS. 9A and 9B show a schematic transmission line representation of the sample accommodator of FIG. 8;

FIGS. 10A and 10B are a set of curves showing real and imaginary parts of the dielectric constant as measured by the apparatus according to the present invention; and

FIG. 11 is a view in top plan of an alternative embodiment of the sample accommodator of FIG. 8 for monitoring the dielectric constant of a constantly flowing fluid.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Of the techniques currently available for the measurement of machinable dielectric samples, the one that has found the widest application in the oil industry is the coaxial sample accommodator technique.

As illustrated in FIG. 1, a coaxial sample accommodator according to the prior art requires a sample 14 to be machined in the form of an annular cylinder which has to conform to very precise dimensions and concentricity. While such requirements are not difficult to satisfy in the case of standard dielectrics, such as plexiglass and the sort of fluorine-containing resins sold under the trademark Teflon, or, with some effort, in the case of well-consolidated rocks of low porosity and homogeneous constitution, it is very hard to satisfy these requirements for the large majority of core sample varieties commonly encountered in the oil industry. Furthermore, it has been shown that when deviations from an ideal annular cylindrical shape occurs, it is necessary to apply large corrections to measured data.

Coaxial sample accommodators have an inner conductor 10 with a diameter a and an outer conductor 12 with a diameter b , as shown in FIG. 1. Sample 14, having an axial dimension X , is coaxial with conductors 10 and 12. Conductors 10 and 12 are connected at either end to a first connector 16 and a second connector 18.

The coaxial sample accommodators currently in use derive their a and b dimensions from the standard 50-ohm connectors available in the market. Commonly, connectors are of the APC-7 and GR-900 types for which the b dimensions are 7 mm and 14 mm, respectively. These small dimensions make machining very difficult, and accentuate any errors in dimension.

However, even when the b dimension is increased to as much as 20.65 mm, close to the largest practical size at which undesirable wave propagation modes may be avoided, the concentricity requirement (the coincidence of the axes of the inner and the outer cylindrical surfaces) is very hard to satisfy for most samples of interest. This requirement for concentricity is easier to achieve for short sample lengths (in the axial direction), but shorter lengths introduce larger errors in the measurements of dielectric properties, and make the measurements uncertain at relatively lower frequencies.

FIG. 2 illustrates a sample accommodator 200 according to the present invention. A conductive strip 20, having flat surfaces 20a and 20b (not shown), is suspended between a first ground plane 22, and a second ground plane 24. Although shown in an exploded view in FIG. 2, when sample accommodator 200 is closed around a sample, ground plane 22 is parallel to and

opposite to surface 20a, as indicated in FIG. 4. Ground plane 24 is parallel to and opposite to surface 20b (not shown).

Strip 20 has a first fluted end 20c (not shown) which forms a part of a first transition 270. Strip 20 also has a second fluted end 20d which forms a part of a second transition 290.

Two sample portions, in the form of blocks A and B, are placed in sample accommodator 200. Each sample block is machined to approximate a rectangular prism. Each has a length dimension X parallel to a long dimension of strip 20. Each has a width dimension Z perpendicular to the long dimension of strip 20 and approximately coextensive with a dimension of ground plane 24 which dimension is perpendicular to the long dimension of strip 20. Finally, each block has a depth dimension Y normal to flat surfaces 20a and 20b.

In order to contain samples A and B within sample accommodator 200, each ground plane is attached to a first end plate 28 at a first end and to a second end plate 26 at a second end. This attachment is accomplished by tightening a screw (not shown) through a hole 28a in end plate 28 and into threaded hole 23a and in ground plane 22, respectively. Screws (not shown) are also tightened through the corresponding pairs of holes 28a and 23b; 26a and 22a; 26b and 22b; 26c and 24c (not shown); 26d and 24d (not shown) 28c (not shown) and 25c (not shown); and 28d and 25d (not shown).

Threads on the outer casing of each of two tuning screws 220c and 220d are respectively engaged with threads in two holes 22c and 22d above opposite ends of strip 20. Likewise, below opposite ends of ground plane 24, threads on tuning screws 240c (not shown) and 240d (not shown) are engaged with threads in holes 24c (not shown) and 24d (not shown).

End plate 26 has a central, round aperture aligned with strip 20 and into which a part of first transition 270 is fitted. Similarly, end plate 28 has a central, round aperture aligned with strip 20 and into which a part of second transition 290 is fitted.

As shown in FIG. 3, wherein structures also found in FIG. 2 are identified by the reference numerals used to identify them therein, each transition, exemplified by transition 290, includes a center conductor contact 291 which has a male threaded end 291a for screwing into a female threaded end 292a of a connector center conductor 292.

Each fluted end of strip 20 has two projections forming a notch, such as notch 20e in fluted end 20d. A male end of center conductor 292b is soldered to fluted end 20d within notch 20e. The two projections of fluted end 20d are placed between the ends of two opposing semi-cylindrical, notched fillers 295a and 295b. The ends of fillers 295a and 295b fit together around the projections of strip 20 so that the combined notches of fillers 295a and 295b form a cylindrical aperture 295c aligned with notch 20e.

The combination of fillers 295a and 295b and fluted end 20d is inserted within the aperture in end plate 28. A retaining ring 294 is placed around fillers 295a and 295b. A central cylindrical aperture in a cylindrical dielectric 293a is passed over end 292a so that connector 293 may be fitted into the aperture in end plate 28. Ring 294 is held in place by gluing it to an inner surface of connector 293 using a suitable glue such as the one sold under the trademark Loctite. Conductor contact end 291a is tightened into female end 292a of center conductor 292 to complete assembly of transition 290.

The same steps are performed to assemble the same sorts of components into transition 270.

Ground planes 22 and 24 and end plates 26 and 28 may be readily machined out of aluminum blocks commonly available to those skilled in the art. Connector parts suitable for use as elements 291, 292, 293 and 294 are available as an MPC 14 (GR-900) connector, part number 2480A, from Maury Microwave Corporation, Cucamonga, California. The gradual "flute" expansion at ends 20c and 20d brings center strip 20 from the dimension of the inner conductor of the GR-900 connector to its full width w. Center strip 20 may be fabricated out of 0.0024 inch-thick brass sheet readily available to those skilled in the art. For example, a strip constructed for a sample accommodator according to the present invention has an impedance of 50 ohms when empty and has a separation between ground planes of 0.6221 in. Fluted portions 20c and 20d of radius 0.375 in. extend for 0.276 in. at either end of strip 20 has a total length of 0.399 inches, a width of 0.847 in. and having a 0.197 inch deep notch at either end L/S band tuning screws suitable for use as elements 220c, 220d, 240c and 240d may be obtained under part number JMC P/N 6965-0 from the Johanson Manufacturing Company, Boonton, NJ. These screws are adjusted to obtain a desired impedance characteristic over a desired frequency band when the sample accommodator is empty.

Fillers 295a and 295b are readily fabricated out of any of a number of fluorine-containing resins, such as those sold under the trademark Teflon, for example. In the case of a 50 ohms stripline, the dielectric constant of the material is approximately 2.

The separation between ground planes 22 and 24 may be chosen to equal the inside diameter of the outer conductor of an unassembled commercial GR-900 rigid line connector, so as to obtain a good electrical match between transitions 270 and 290 and strip 20. Strip 20 is chosen to be paper thin (i.e., $t < w$), in order to eliminate one dimension from the calculations. The strip width w may be chosen to obtain a 50-ohm characteristic impedance for the empty sample accommodator. After calculating the theoretical value of w, a trial-and-error technique may be used to trim this width in order to fine-adjust the impedance.

As shown in FIG. 2, samples A and B are cut in the form of bars of rectangular cross-section. Two such bars are used for each sample. They fit in the sample accommodator in the way shown in FIG. 2. The X-dimension of each bar enters into the calculations. Thus, it is desirable that the X-dimension be as nearly the same for the two bars as possible. The actual value of this dimension is not critical, as long as it is known accurately. For each bar the y-dimension, corresponding to the separation between each ground plane and an opposing surface of strip 20, has to be such that the sample fits snugly in the accommodator. The z-dimension of the sample accommodator, is somewhat arbitrary, but it is important that this dimension be large enough so that fringing fields 40, as shown in FIG. 4, are contained within the sample blocks. In FIG. 4, structures also found in FIG. 2 are identified by the reference numerals used to identify them therein.

As shown in the partial cross-section of FIG. 5, wherein structures also found in FIG. 2 are identified by the reference numerals used to identify them therein, an empty sample accommodator according to the present invention is in the form of a transmission line, where the

central conductor is a metallic strip 20, sandwiched between two conducting planes 22 and 24. A dielectric material may be placed between each surface of strip 20 and the plane opposite to it. Assuming that the width w of strip 20 is large enough so that the fringing fields at the edges of strip 20 do not interact, the characteristic impedance Z_0 of a dielectric-filled line is:

$$Z_0 = \frac{94.15}{\frac{w/b}{1 - (t/b)} + \frac{C_f}{0.0885 \epsilon_r}} \frac{1}{\sqrt{\epsilon_r}} \text{ ohms} \quad (1)$$

where the capacitance C_f due to fringing fields is given by

$$C_f = \frac{0.0885 \epsilon_r}{\pi} \left\{ \left[\frac{2}{1 - (t/b)} \right] \ln \left[\frac{1}{1 - (t/b)} + 1 \right] - \left[\frac{1}{1 - (t/b)} \right] - 1 \ln \left[\frac{1}{1 - (t/b)^2} - 1 \right] \right\} \quad (2)$$

in picofarad/cm and where:

ϵ_r = the permittivity of the dielectric;

w = the width of strip 20;

t = the thickness of strip 20; and

b = the distance between planes 22 and 24.

Dielectric constants are obtained according to the method of the present invention from measurements of scattering parameters of a sample by connecting transitions 270 and 290 to ports of an appropriate apparatus. In the frequency domain measurements may be made by using a network analyzer, such as the Model 8505A Automatic Network Analyzer System 300 available from Hewlett-Packard, Inc., Palo Alto, CA. In the time-domain a waveform processing system, such as the Model 7854/7S12 Time-Domain Reflectometer available from Tektronix, Inc., Beaverton, Oregon, may be used to make measurements with various pulses generator/sampler combinations. Either technique measures the S parameters (scattering parameters) S_{11} and S_{21} (or, equivalently, S_{22} and S_{12}). These are complex quantities giving the amplitudes and phases of the signals reflected from and transmitted through the sample, respectively. From these parameters, the complex dielectric permittivity (as well as the magnetic permeability) of the sample can be calculated, given the width of the sample in the direction of propagation which corresponds to the X-dimension in FIG. 2.

The network formed by the sample accommodator and attached measurement apparatus may be diagrammed as shown in FIG. 6.

The two-port network illustrated in FIG. 6 may be described by the following equations:

$$b_1 = S_{11} a_1 + S_{12} a_2 \quad (3)$$

$$b_2 = S_{21} a_1 + S_{22} a_2 \quad (4)$$

where:

a_1 = a voltage measured across source impedance Z_s looking into a two-port network 60 at 61;

a_2 = a voltage measured across a impedance Z_L looking into network 60 at 62;

b_1 = a source voltage measured looking out of network 60 at 64; and

b_2 = a voltage measured looking out of network 60 at 63 and where S_{11} , S_{22} , S_{12} , and S_{21} are the S parameters (scattering parameters) which are defined as follows:

$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} \quad (5)$$

= an input reflection coefficient with the output port terminated in a matched load ($Z_L = Z_0$ sets $a_2 = 0$);

$$S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0} \quad (6)$$

= an output reflection coefficient with the input port terminated in a matched load ($Z_s = Z_0$ and $V_s = 0$ set $a_1 = 0$ where V_s is a source voltage);

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0} \quad (7)$$

= a forward transmission gain with the output port terminated in a matched load; and

$$S_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0} \quad (8)$$

= a reverse transmission gain with the input port terminated in a matched load.

FIG. 7A shows a diagrammatic, edge-on view of two rectangular slabs of rock inserted into a strip transmission line. The equivalent transmission line model of this view is shown in FIG. 7B. FIG. 7C depicts the transmission line terminated in a matched load and FIG. 7D is an equivalent circuit for the circuit in FIG. 7C. An air region has a magnetic permeability μ_0 and electric permittivity ϵ_0 while a rock region has a permeability μ_2 and a permittivity ϵ_{c2} . This permittivity is a complex quantity defined by

$$\epsilon_{c2} = \epsilon_0 \left(\epsilon_{r2} - j \frac{\sigma_2}{\omega \epsilon_0} \right) \quad (9)$$

where:

ϵ_{r2} = the relative dielectric constant of a rock sample, σ_2 = the conductivity of the rock sample, and ω = the angular frequency of an electromagnetic wave propagating through the line.

In the equivalent transmission line model of FIG. 7B, Z_0 and Z_2 are the impedances of the air portion and rock-filled portions of the line, respectively, and k_2 the propagation constant. These quantities are defined as follows:

$$Z_0 = \sqrt{\mu_0} \left[\frac{83,988}{\frac{w/b}{1 - (t/b)} + \frac{C_f}{0.0885}} \right] \text{ ohms;} \quad (10)$$

$$Z_2 = \frac{\sqrt{\mu_2 \epsilon_0}}{\epsilon_{c2}} \left[\frac{83,988}{\frac{w/b}{1 - (t/b)} + \frac{C_f \epsilon_0}{0.0885 \epsilon_{r2}}} \right] \text{ ohms; and} \quad (11)$$

-continued

$$k_2 = \omega \sqrt{\mu_2 \epsilon_{c2}}$$

where:

 ϵ_{c2} = the permittivity of the sample; C_f = the fringe capacitance given by

$$C_f = \frac{0.0885 \epsilon}{\pi \epsilon_0} \left\{ \frac{2}{1 - (t/b)} \ln \left[\frac{1}{1 - (t/b)} + 1 \right] - \right.$$

$$\left. \frac{1}{1 - (t/b)} - 1 \ln \left[\frac{1}{1 - (t/b)^2} - 1 \right] \right\}$$

in picofarads/cm;

ϵ = the permittivity of the medium in the stripline sample accommodator, either ϵ_0 for the Z_0 portion or $\epsilon_0 \epsilon_{r2}$ for the Z_2 portion; and where all other constants and variables are as defined above.

For a two-port network we need only consider the input reflection coefficient, S_{11} , and the forward transmission gain, S_{21} (or, alternatively, S_{12} and S_{22}). Since they are defined with the output terminated in a matched load, we consider the case illustrated in FIG. 7C where the input impedance $Z_{in}(W)$ between $W = -1$ and $W = 0$ is given by

$$Z_{in}(W) = \frac{1 + R_{20} e^{j2k_2 W}}{1 - R_{20} e^{j2k_2 W}} \quad (14)$$

where

$$R_{20} = \frac{Z_0 - Z_2}{Z_0 + Z_2}, \quad (15)$$

which is the reflection coefficient of the line at $W = 0$. W = the distance from the edge at which an incident wave leaves the sample in the direction of propagation (as indicated by the arrow in FIG. 7B); l = the length of the path through the sample in the direction of propagation; and where all other constants and variables are as defined above.

Using the definition of S_{11} in Equation (5), the model in FIG. 7C can be simplified to that shown in FIG. 7D so that the expression for S_{11} becomes

$$S_{11} = \frac{Z_{in}(-l) - Z_0}{Z_{in}(-l) + Z_0} \quad (16)$$

where all constants and variables are as defined above.

Inserting Equation (14) into equation (16) with $W = -1$ gives

$$S_{11} = \frac{R_{02} + R_{20} e^{-j2k_2 l}}{1 + R_{02} R_{20} e^{-j2k_2 l}} \quad (17)$$

where

$$R_{02} = \frac{Z_2 - Z_0}{Z_2 + Z_0}; \text{ and} \quad (18)$$

where all other constants and variables are as defined above.

If the incident wave has an amplitude of unity and its phase at $W = -1$ is zero, then from FIG. 7C, the voltage V_1 between $W = -1$ and $W = -\infty$ is

$$V_1(W) = e^{-jk_2(W+l)} + S_{11} e^{jk_2(W+l)} \quad (19)$$

and the voltage V_2 between $W = 0$ and $W = -1$ is

$$V_2(W) = V^+ e^{-jk_2 W} + V^- e^{jk_2 W} \quad (20)$$

where all constants and variables are as defined above.

Upon satisfying the boundary condition at $W = -1$, $V_1(-1) = V_2(-1)$ we have

$$1 + S_{11} = V^+ e^{jk_2 l} (1 + R_{20} e^{-jk_2 l}) \quad (21)$$

where

$$R_{20} = V^- / V^+, \quad (b \ 22)$$

where

$$V^+ = \frac{(1 + S_{11}) e^{-jk_2 l}}{1 + R_{20} e^{-jk_2 l}}, \text{ and} \quad (23)$$

where all constants and variables are as defined above.

From the definition of S_{21} ,

$$S_{21} = \frac{V_2(0)}{1} = V^+ + V^- = V^+ (1 + R_{20}). \quad (24)$$

The "1" in the denominator represents the unit amplitude and zero phase of the incident wave and $V_2(0)$ is the voltage measured at $W = 0$. All other constants and variables are as defined above. Now we substituted Equations (22) and (23) into Equation (24) and obtain

$$S_{21} = \frac{(1 + S_{11}) e^{-jk_2 l} (1 + R_{20})}{1 + R_{20} e^{-jk_2 l}}. \quad (25)$$

combining Equation (17) with Equation (25) yields

$$S_{21} = \frac{(1 - R_{02}^2) e^{-jk_2 l}}{1 - R_{02}^2 e^{-j2k_2 l}}. \quad (26)$$

We can simplify this expression by letting

$$q = e^{-jk_2 l}, \text{ and} \quad (27)$$

$$R = R_{02} = -R_{20} = \frac{Z_2 - Z_0}{Z_2 + Z_0}. \quad (28)$$

Consequently, Equations (17) and (26) may be rewritten as

$$S_{11} = \frac{R(1 - q^2)}{1 - R^2 q^2} \quad (29)$$

and

$$S_{21} = \frac{(1 - R^2) q}{1 - R^2 q^2}. \quad (30)$$

Adding Equations (29) and (30) we obtain

$$S_{11} + S_{21} = \frac{R + q}{1 + Rq}$$

Solving for q gives

$$q = \frac{(S_{11} + S_{21}) - R}{1 - (S_{11} + S_{21})R}$$

Equations (29) and (30) also give

$$S_{11} + S_{21} + 1 = \frac{(1 + R)(1 + q)}{1 + Rq}$$

$$S_{11} + S_{21} - 1 = \frac{(R - 1)(1 - q)}{1 + Rq}$$

$$S_{11} - S_{21} + 1 = \frac{(1 + R)(1 - q)}{1 - Rq}$$

$$S_{11} - S_{21} - 1 = \frac{(R - 1)(1 + q)}{1 - Rq}$$

which are used to write

$$\left[\frac{S_{11} + S_{21} + 1}{S_{11} + S_{21} - 1} \right] \left[\frac{S_{11} - S_{21} + 1}{S_{11} - S_{21} - 1} \right] = \frac{1 + 2R + R^2}{1 - 2R + R^2}$$

or,

$$S_{11}R^2 - (S_{11}^2 - S_{21}^2 + 1)R + S_{11} = 0.$$

Solving for R we have

$$R = \frac{(S_{11}^2 - S_{21}^2 + 1) - A}{2S_{11}}$$

where

$$A = [(S_{11} + S_{21} + 1)(S_{11} + S_{21} - 1) \\ (S_{11} - S_{21} + 1)(S_{11} - S_{21} - 1)]^{\frac{1}{2}}$$

and where all other constants and variables are as defined above.

The quantity q is obtained by substituting Equation (27) into Equation (34) such that

$$q = \frac{(S_{21}^2 - S_{11}^2 + 1) - A}{2S_{21}}$$

Using Equation (27) we have

$$k_2 = \frac{j \ln(q)}{l}$$

and from Equation (28) we have

$$Z_2 = Z_0 \frac{1 + R}{1 - R}$$

If we recall that $k_2 = \omega \sqrt{\mu_2 \epsilon_2}$, we can use Equation (40) to write

$$\sqrt{\mu_2 \epsilon_2} = \frac{j \ln(q)}{\omega l}$$

Substituting Equations (10) and (11) into Equation (43) gives

$$\sqrt{\frac{\epsilon_{c2}}{\mu_2}} = \sqrt{\frac{\epsilon_0}{\mu_0}} \frac{1 - R}{1 + R} \quad (31)$$

The complex permittivity of the rock, ϵ_{c2} , is found from Equations (44) and (45) to be

$$\epsilon_{c2} = \left(\sqrt{\frac{\epsilon_0}{\mu_0}} \left(\frac{1}{\omega l} \right) j \ln(q) \left[\frac{1 - R}{1 + R} \right] \right)^2 \quad (32)$$

where R and q are complex numbers. Comparison of this result with Equation 9 gives:

$$\epsilon_{r2} = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \frac{1}{\omega l} \operatorname{Re} \left[j \ln(q) \left(\frac{1 - R}{1 + R} \right) \right], \text{ and} \quad (33)$$

$$\sigma_2 = - \sqrt{\frac{\epsilon_0}{\mu}} \frac{1}{l} \operatorname{Im} \left[j \ln(q) \left(\frac{1 - R}{1 + R} \right) \right] \quad (34)$$

Thus, q and R are determined from the S parameters using Equations (39) and (41), and the dielectric constant and conductivity are calculated from Equations (47) and (48).

As illustrated in FIG. 8, for measurement of liquid samples, hollow compartments 80 and 81 may be made of materials sold under the trademarks made of standard dielectric materials (e.g., Teflon and Rexolite) and having a rectangular cross-section may be used in place of the solid sample bars shown in FIG. 2. Each of these compartments accommodates an equal portion of the sample and is equipped with inlet and outlet holes (not shown) for introducing liquids into the compartments. By knowing the dielectric permittivity and the wall thickness (in the direction of propagation 82) of the compartment, its effect may be removed from the measurement, and thus, the dielectric permittivity of the liquid derived. The filler and drainage holes (not shown) in the compartments also allow the insertion of a temperature probe (not shown).

The measurement technique for solid samples may be readily extended to liquid samples. In this case liquid compartments are placed parallel to each planar surface of strip 20. A transmitted wave must now pass through the container's walls, one wall before entering the sample and one after leaving it as indicated in FIG. 8. End walls 83 and 84 of compartment 80 are away from the stripline so that they do not interfere with wave propagation.

In FIG. 9A, μ_1 and ϵ_1 are the magnetic permeability and dielectric permittivity, respectively, of the walls of the liquid container. These values can be measured using the dry sample theory where a sample made of the same material as the liquid container is measured in the stripline sample accommodator. The permeability and permittivity of the liquid sample are denoted by μ_2 and ϵ_{c2} , respectively.

FIG. 9B is the equivalent transmission line model of FIG. 9A. The values k_1 and Z_1 are the propagation constant and characteristic impedance of the wall portion of the sample accommodator. They can be obtained from dielectric measurements of the wall material.

As the impedances and propagation constants may be expressed as follows:

$$Z_1 = \frac{\sqrt{\mu_1 \epsilon_0}}{\sqrt{\epsilon_{c1}}} \frac{83,988}{\frac{(w/b)}{1 - (t/b)} + \left(\frac{C_f \epsilon_0}{0.0885 \epsilon_{c1}} \right)}$$

$$k_1 = \omega \sqrt{\mu_1 \epsilon_{c1}}$$

$$Z_2 = \frac{\sqrt{\mu_2 \epsilon_0}}{\sqrt{\epsilon_{c2}}} \frac{83,988}{\frac{(w/b)}{1 - (t/b)} + \frac{C_f \epsilon_0}{0.0885 \epsilon_{c2}}}$$

$$k_2 = \omega \sqrt{\mu_2 \epsilon_{c2}}$$

where:

b=the distance between ground plates;

w=the width of strip 20;

t=thickness of strip 20;

ϵ_{c1} =the permittivity of the liquid container;

μ_1 =the permeability of the liquid container;

ϵ_{c2} =the permittivity of the liquid sample;

μ_2 =the permeability of the liquid sample;

ω =the angular frequency of the wave; and

C_f is the fringe capacitance given by

$$C_f = \frac{0.0885 \epsilon}{\pi} \left\{ \frac{2}{1 - (t/b)} \ln \left(\frac{1}{1 - (t/b)} + 1 \right) - \left(\frac{1}{1 - (t/b)} - 1 \right) \ln \left(\frac{1}{[1 - (t/b)]^2} - 1 \right) \right\} \quad (53)$$

in picofarads/cm where ϵ is ϵ_{c1} for the Z_1 portion and ϵ_{c2} for the Z_2 portion.

The line is divided into five regions and $W=d$ is taken as a reference point where the incident wave (which is assumed to have an amplitude of 1) has a phase of zero as in FIG. 9. W is the distance from the boundary of at which an incident wave enters a liquid sample in the direction of propagation (as shown by arrow 82 in FIG. 8). If d is the wall thickness of liquid container 80 and l is the length of the liquid sample in the direction of propagation, then the voltages and currents in the five regions may be written as follows:

Region 1: $W \leq -d$

$$V_0(W) = e^{-jk_0(W+d)} + S_{11}e^{jk_0(W+d)} \quad (54)$$

$$I_0(W) = \frac{1}{Z_0} [e^{-jk_0(W+d)} - S_{11}e^{jk_0(W+d)}] \quad (55)$$

Region 2: $-d \leq W \leq 0$

$$V_1(W) = Ae^{-jk_1W} + Be^{jk_1W} \quad (56)$$

$$I_1(W) = \frac{1}{Z_1} [Ae^{-jk_1W} - Be^{jk_1W}] \quad (57)$$

Region 3: $0 \leq W \leq l$

$$V_2(W) = Ce^{-jk_2W} + De^{jk_2W} \quad (58)$$

$$I_2(W) = \frac{1}{Z_2} [Ce^{-jk_2W} - De^{jk_2W}] \quad (59)$$

Region 4: $l \leq W \leq l+d$

$$V_3(W) = Ee^{-jk_1W} + Fe^{jk_1W} \quad (60)$$

-continued

$$I_3(W) = \frac{1}{Z_1} [Ee^{-jk_1W} - Fe^{jk_1W}] \quad (61)$$

5 Region 5: $l+d \leq W$

$$V_4(W) = S_{21}e^{-jk_0(W-l-d)} \quad (62)$$

$$I_4(W) = \frac{1}{Z_0} [S_{21}e^{-jk_0(W-l-d)}] \quad (63)$$

(51) 10

where A through F are constant coefficients and S_{21} and S_{11} are measured scattering parameters.

(52) 15 At each interface, the boundary conditions consisting of continuity in the phase and amplitude of the voltages and currents must be satisfied. Consequently, at $W=-d$ we have

$$V_0(-d) = V_1(-d) \quad (64)$$

$$20 \quad I_0(-d) = I_1(-d) \quad (65)$$

From Equations (54) and (57)

$$1 + S_{11} = Ae^{jk_1d} + Be^{-jk_1d} \quad (66)$$

$$25 \quad \frac{1 - S_{11}}{Z_0} = \frac{Ae^{jk_1d} - Be^{-jk_1d}}{Z_1} \quad (67)$$

Solving these equations for A and B gives us

$$A = \frac{1}{2} e^{-jk_1d} \left[(1 + S_{11}) + (1 - S_{11}) \frac{Z_1}{Z_0} \right] \quad (68)$$

$$B = \frac{1}{2} e^{jk_1d} \left[(1 + S_{11}) - (1 - S_{11}) \frac{Z_1}{Z_0} \right] \quad (69)$$

Similarly, at the point $W=l+d$, we have

$$E = \frac{1}{2} e^{jk_1(l+d)} S_{21} \left(1 + \frac{Z_1}{Z_0} \right) \quad (70)$$

$$F = \frac{1}{2} e^{-jk_1(l+d)} S_{21} \left(1 - \frac{Z_1}{Z_0} \right) \quad (71)$$

For $W=0$

$$C = \frac{1}{2} \left[\left(1 + \frac{Z_2}{Z_1} \right) A + \left(1 - \frac{Z_2}{Z_1} \right) B \right] \quad (72)$$

$$D = \frac{1}{2} \left[\left(1 - \frac{Z_2}{Z_1} \right) A + \left(1 + \frac{Z_2}{Z_1} \right) B \right] \quad (73)$$

For $W=l$ we have

$$60 \quad C = \frac{1}{2} e^{jk_2l} \left[\left(1 + \frac{Z_2}{Z_1} \right) Ee^{-jk_1l} + \left(1 - \frac{Z_2}{Z_1} \right) Fe^{jk_1l} \right] \quad (74)$$

$$55 \quad D = \frac{1}{2} e^{-jk_2l} \left[\left(1 - \frac{Z_2}{Z_1} \right) Ee^{-jk_1l} + \left(1 + \frac{Z_2}{Z_1} \right) Fe^{jk_1l} \right] \quad (75)$$

Now the product CD obtained from Equations (72) and (73) must equal that obtained from Equations (74) and (75).

$$\begin{aligned} & \left[\left(1 + \frac{Z_2}{Z_1} \right)^A + \right. \\ & \left. \left[\left(1 - \frac{Z_2}{Z_1} \right)^B \right] \left[\left(1 - \frac{Z_2}{Z_1} \right)^A + \left(1 + \frac{Z_2}{Z_1} \right)^B \right] = \right. \\ & \left[\left(1 + \frac{Z_2}{Z_1} \right)^{Ee^{-jk_1 l}} + \right. \\ & \left. \left(1 - \frac{Z_2}{Z_1} \right)^{Fe^{jk_1 l}} \right] \left[\left(1 - \frac{Z_2}{Z_1} \right)^{Ee^{-jk_1 l}} + \right. \\ & \left. \left(1 + \frac{Z_2}{Z_1} \right)^{Fe^{jk_1 l}} \right] \end{aligned}$$

We can simplify this equation by letting

$$\begin{aligned} X &= Z_2/Z_1 \\ G &= Ee^{jk_1 l} \\ H &= Fe^{jk_1 l} \end{aligned}$$

Thus Equation (76) becomes

$$[(1+X)A + (1-X)B][[(1-X)A + (1+X)B] = [(1+X)G + (1-X)H][[(1-X)G + (1+X)H]] \quad (77)$$

After some rearrangement of this expression we have:

$$[(G-H)^2 - (A-B)^2]X^2 = (G+H)^2 - (A+B)^2 \quad (78)$$

Consequently,

$$X = \frac{Z_2}{Z_1} = \left[\frac{(A+B)^2 - (G+H)^2}{(A-B)^2 - (G-H)^2} \right]^{\frac{1}{2}} \quad (79)$$

since the right hand sides of Equations 72 and 74 must be equal, we can write

$$q = e^{-jk_2 l} = \frac{(1+X)G + (1-X)H}{(1+X)A + (1-X)B} \quad (80)$$

The quantities A, B, G, H, and X are known, so q is known. The propagation constant of the strip transmission line filled with liquid is:

$$k_2 = \omega \sqrt{\mu_2 \epsilon_{c2}} = \frac{j \ln(q)}{l} \quad (81)$$

so

$$\sqrt{\mu_2 \epsilon_{c2}} = \frac{j \ln(q)}{\omega l} \quad (82)$$

Recalling that in air the characteristic impedance for a stripline transmission line is given by

$$Z_0 = \sqrt{\mu_0} \frac{83,988}{1 - (t/b) + \frac{C_f}{0.0885}} \quad (83)$$

and combining this with Equation (51) leads to

$$\frac{Z_0}{Z_2} = \sqrt{\frac{\epsilon_{c2}}{\mu_2}} \sqrt{\frac{\mu_0}{\epsilon_0}} \quad (84)$$

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thus

$$\sqrt{\frac{\epsilon_{c2}}{\mu_2}} = \frac{Z_0}{Z_2} \sqrt{\frac{\epsilon_0}{\mu_0}} \quad (85)$$

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Combining Equation (82) with Equation (85) gives

$$\epsilon_{c2} = \frac{j \ln(q)}{\omega l} \frac{Z_0}{Z_2} \frac{\sqrt{\epsilon_0}}{\mu_0} \quad (86)$$

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From the basic definition of complex permittivity given in Equation (9), the dielectric constant and conductivity for any liquid can be obtained from Equation (86) as follows:

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$$\epsilon_{r2} = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \frac{1}{\omega l} \operatorname{Re} \left[j \ln(q) \frac{Z_0}{Z_2} \right] \quad (87)$$

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$$\sigma_2 = - \frac{\sqrt{\epsilon_0}}{\mu_0} \frac{1}{l} \operatorname{Im} \left[j \ln(q) \frac{Z_0}{Z_2} \right] \quad (88)$$

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FIG. 10 shows data on Berea sandstones, saturated with distilled water and with brines of various salinities. These data are in good agreement with published results. The critical sample dimension is the x-dimension shown in FIG. 2. As indicated in Equation (44), the calculated permittivity is inversely proportional to this dimension. However, this dimension can be machined and measured precisely enough so that it is not a significant source of error.

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Based on the above considerations, and also on experience with measurements of standard solids and liquids, it is believed that the accuracy in the measurement of the complex permittivity for a prototype sample accommodator is typically $\pm 5\%$ in the range 20-1300 MHz, degrading to $\pm 10\%$ for very lossy samples (e.g. strong brines and some alcohols). It is believed here is room for further improvement in the design (e.g. the transition), leading to even higher accuracies over broader bands.

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While the present invention has been described in terms of a preferred embodiment, further modifications and improvements will occur to those skilled in the art. For example, sample compartments, the apparatus according to the present invention, may be modified to measure the dielectric constant of a flowing fluid.

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In FIG. 11, sections of pipe segments 110 and 111 (not shown) are rectangular cross-section similar to containers 80 and 81. Each of segments 110 and 111 is connected to an in-line mixer 113 by way of small diameter pipes 112. In-line mixer 113 has an input connected to a feed line 114 which may be connected to a source of a flowing fluid. A return line is connected to an end of each of segments 110 and 111 which end is directly opposite to the end connected to lines 112. By connecting transitions 270 and 290, as described for the embodiment of the present invention having sample containers 80 and 81, the complex dielectric constant of the flowing fluid may be continually monitored. Such apparatus may be used, for example, to monitor salinity of a flow-

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ing brine (such as produced water) or to measure the water/oil fraction in a small diameter pipeline.

I desire it to be understood, therefore, that the present invention is not limited to the particular form shown and that I intend in the appended claims to cover all such equivalent variations which come within the scope of the invention as claimed.

What is claimed is:

1. Stripline apparatus for the measurement of scattering parameters of a core sample comprising:

(a) a sample holder comprising:

a single conductive strip having two planar surfaces; and

two ground planes, each of said ground planes being positioned opposite to and parallel to a different one of said planar surfaces of said strip, wherein said holder has a characteristic impedance unchanging along its length when said holder is empty of samples;

(b) means for containing the core sample in two portions between each of said ground planes and said surface opposite to it, said sample portions having a z dimension large enough so that the main electric field and the fringing electric field from said conductive strip are substantially contained within the portions;

(c) means for measuring amplitudes and phase shifts of the signals reflected from and transmitted through the core sample.

2. Apparatus as recited in claim 1 wherein said means for containing comprises two endplates, each of said endplates being connected to each ground plane and being electrically isolated from said strip.

3. Apparatus as recited in claim 2 wherein said means for containing further comprises two coaxial cable connectors, each coaxial cable connector being connected to different end of said strip.

4. Apparatus as recited in claim 3 wherein each end of said strip is fluted.

5. Apparatus as recited in claim 2 wherein said means for containing further comprises two compartments, each of said compartments being positioned between a different surface of said strip and one of said ground planes.

6. Apparatus as recited in claim 5 wherein said means for containing further comprises two coaxial cable connectors, each coaxial cable connector being connected to different end of said strip.

7. Apparatus as recited in claim 6 wherein each end of said strip is fluted.

8. Apparatus as recited in claim 7 wherein said means for containing further comprises two pipe segments compartments, each of said pipe segments being positioned between a different surface of said strip and one of aid ground planes.

9. Apparatus as recited in claim 8 wherein said means for containing further comprises two coaxial cable connectors, each coaxial cable connectors being connected to different end of said strip.

10. Apparatus as recited in claim 9 wherein each end of said strip is fluted.

11. A method for measuring scattering parameters of core samples comprising the steps of:

(a) placing each of two core sample portions between a different planar surface of a conductive strip and one of two ground planes, wherein said conductive strip and two ground planes form a sample holder having a characteristic impedance unchanging along its length when said sample holder is empty of samples, said core samples having dimensions large enough so that the main electric field and the fringing fields from said conductive strip are contained within said core sample portions; and

(b) calculating the amplitude and phase shift parameters of said core sample portions in the frequency domain based on reflected and transmitted signal data from the samples.

12. The method as recited in claim 11 wherein said placing step comprises the step of introducing each core sample portion in the form of a block of rectangular cross-section between a different planar surface of the conductive strip and one of the two ground planes.

13. The method as recited in claim 11 wherein said placing step comprises the step of introducing each core sample portion in liquid form into one of two compartments, each compartment being located between a different planar surface of the conductive strip and one of the two ground planes.

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US005132623A

United States Patent [19]

De et al.

[11] **Patent Number:** 5,132,623[45] **Date of Patent:** Jul. 21, 1992**[54] METHOD AND APPARATUS FOR
BROADBAND MEASUREMENT OF
DIELECTRIC PROPERTIES**

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[73] Assignee: **Chevron Research and Technology
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[21] Appl. No.: **616,121**

[22] Filed: **Nov. 20, 1990**

[51] Int. Cl.⁵ **G01V 3/30; G01V 3/18**

[52] U.S. Cl. **324/338; 324/632;
324/639; 343/789**

[58] Field of Search **324/338, 632, 639, 641;
343/700 MS, 789**

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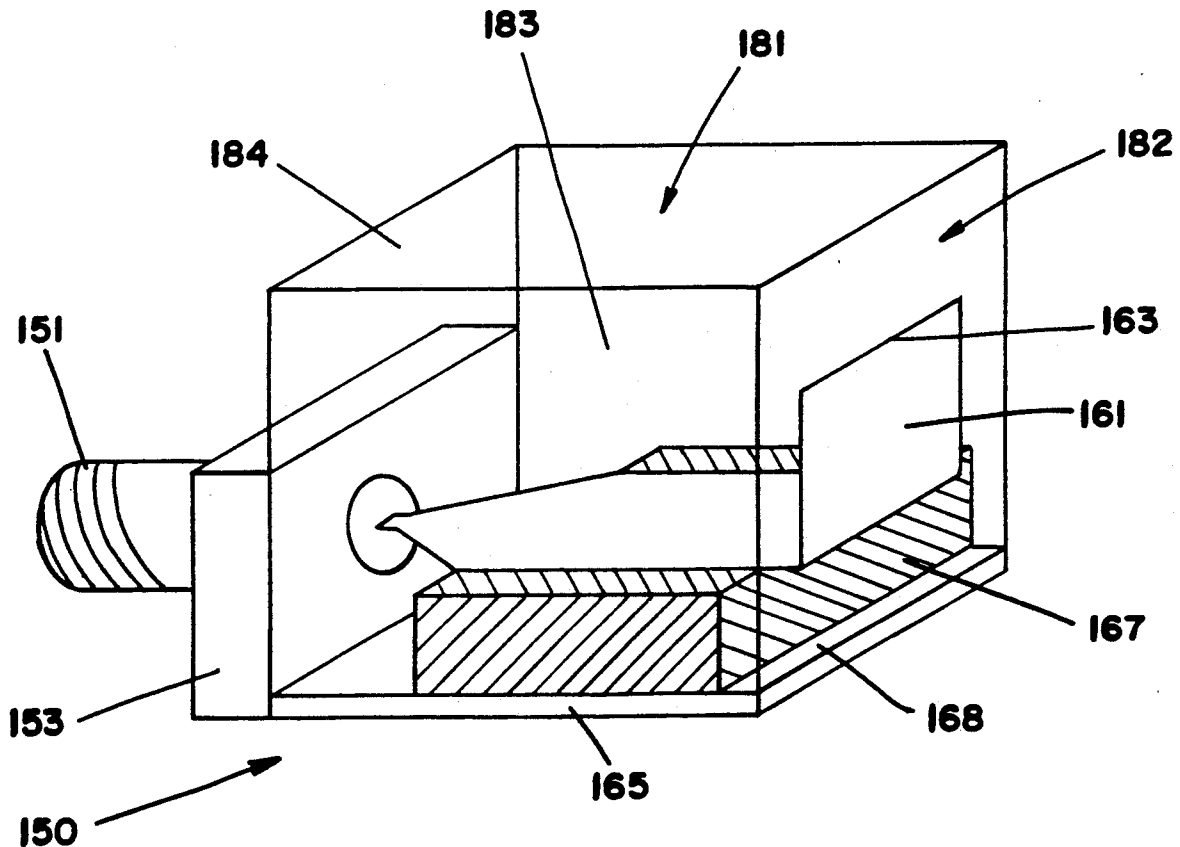
Primary Examiner—Kenneth A. Wieder

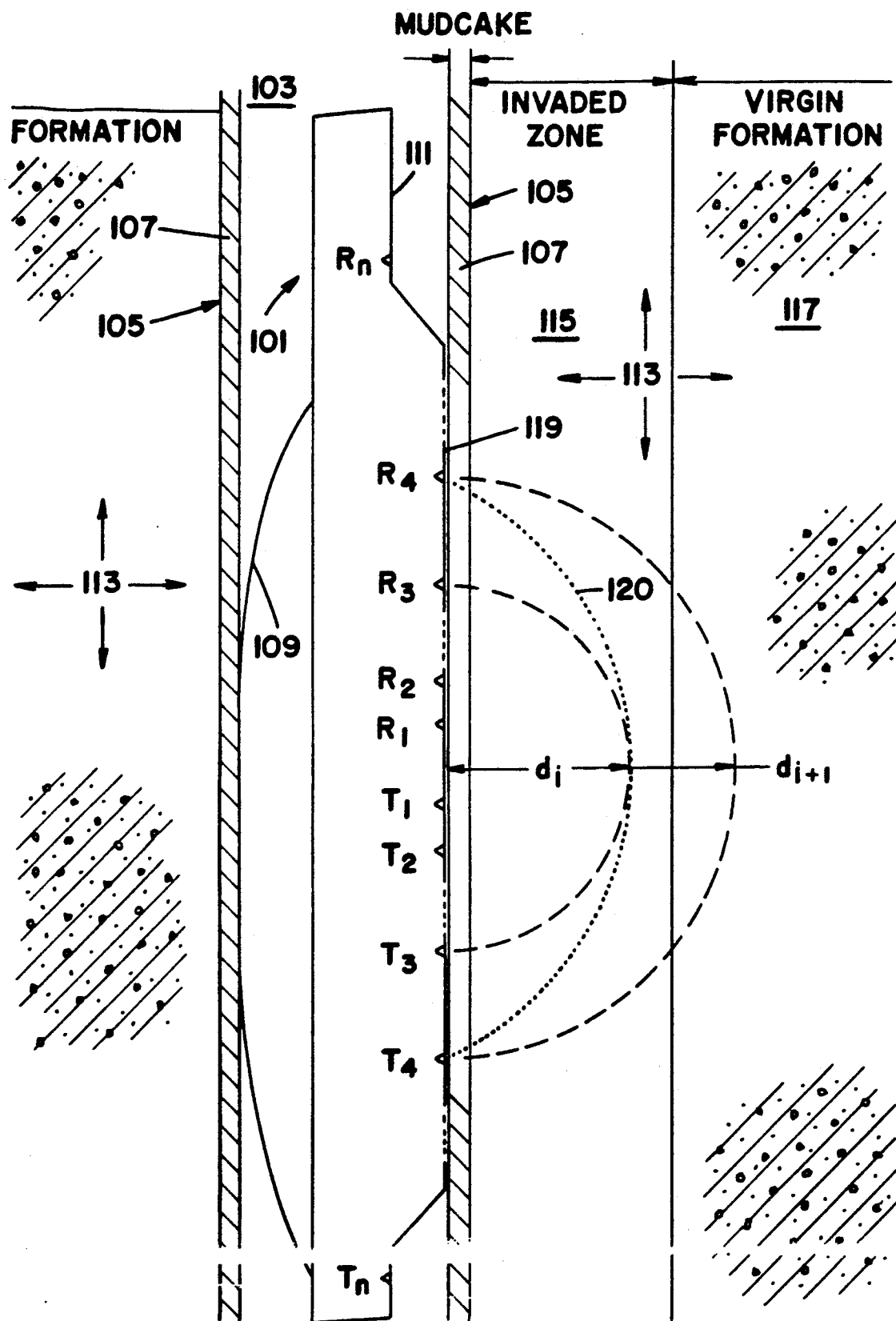
Assistant Examiner—Jose M. Solis

Attorney, Agent, or Firm—Edward J. Keeling; Matt W. Carson

[57] ABSTRACT

A method and apparatus measures dielectric properties over a broad range of frequencies. The functions of various resistivity and dielectric constant measuring devices such as logging tools are combined in a single tool. A measuring tool includes novel transmitting and receiving antennas. Electromagnetic energy flows to a transmitting antenna. A stripline adapter permits transmission to a stripline having a metallic central strip. A strip face is bent at approximately right angles, and has a length that is compatible with the desired frequency coverage. A ground plane extends from the stripline adapter to the right angle bend, and a void exists between the center strip and the ground plane. A dielectric is positioned to nearly fill the void. The antennas are positioned so that the strip face lies flush with the tool face, to permit electromagnetic energy to be transmitted into and out of the material to be analyzed. An enclosure comprised of four metallic walls surrounds the stripline, and is in electrical contact with the ground plane and the stripline adapter. The invention permits an analysis of the fluids in the material as well.

51 Claims, 8 Drawing Sheets



FIG_1

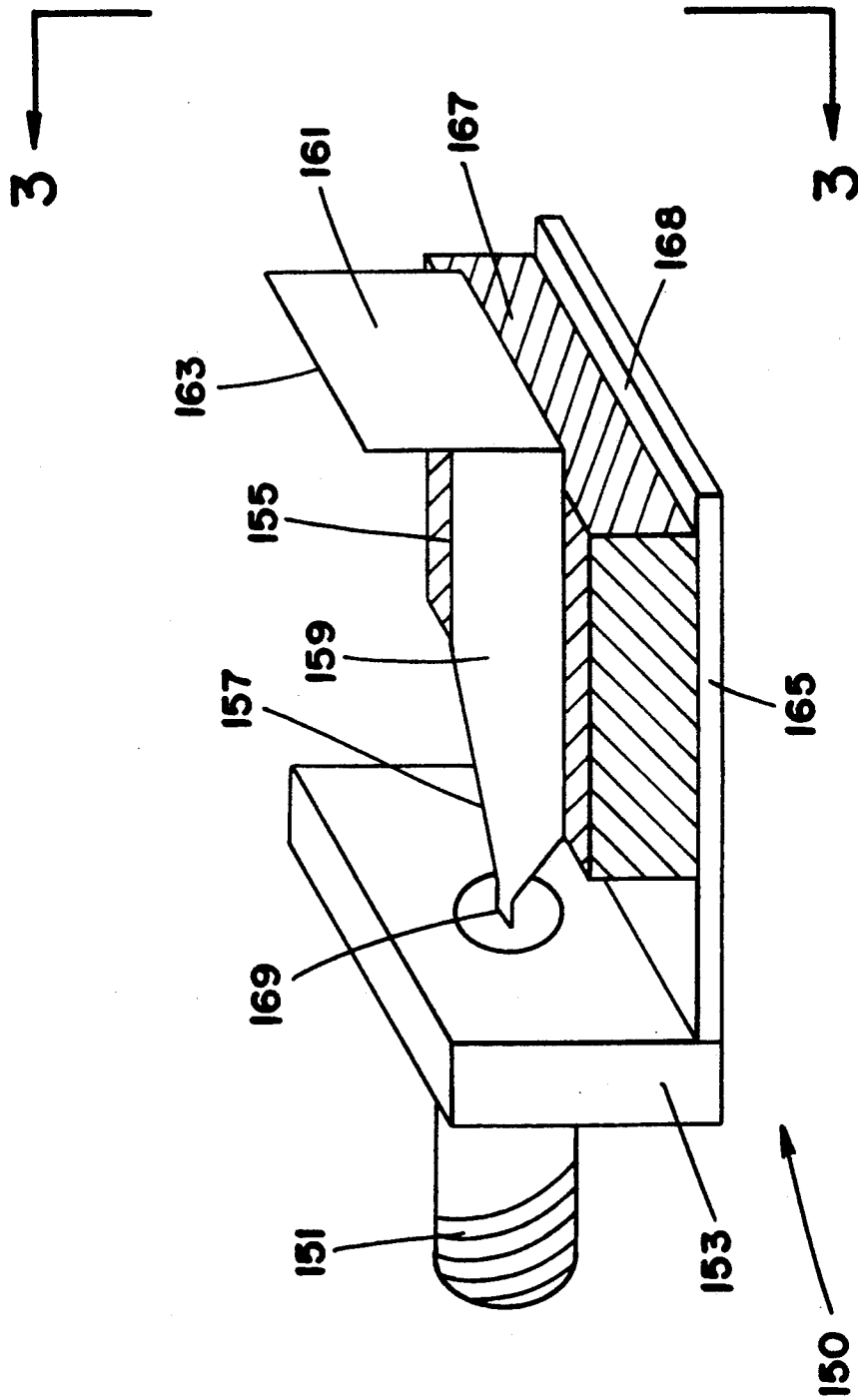


FIG-2

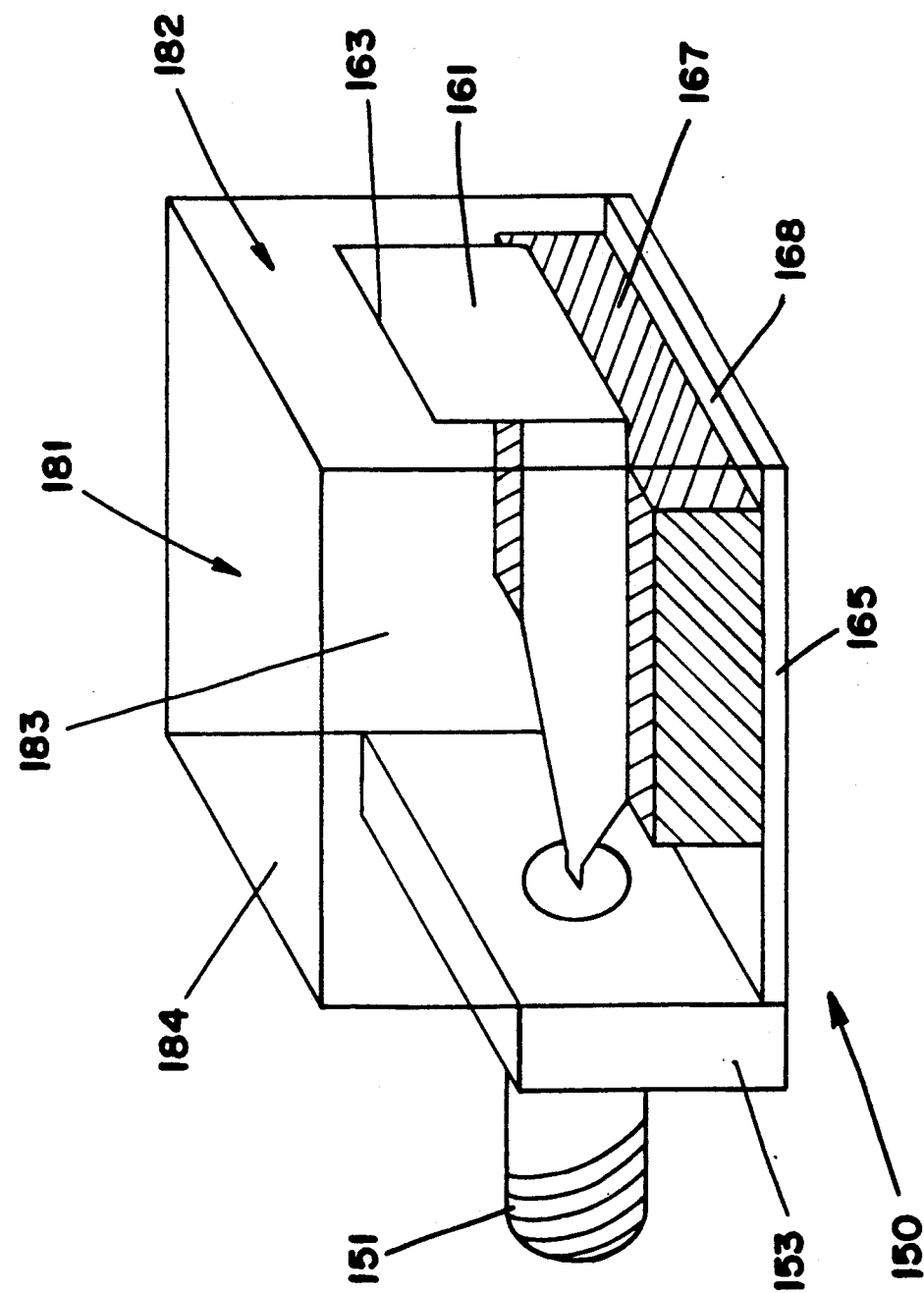


FIG-2A

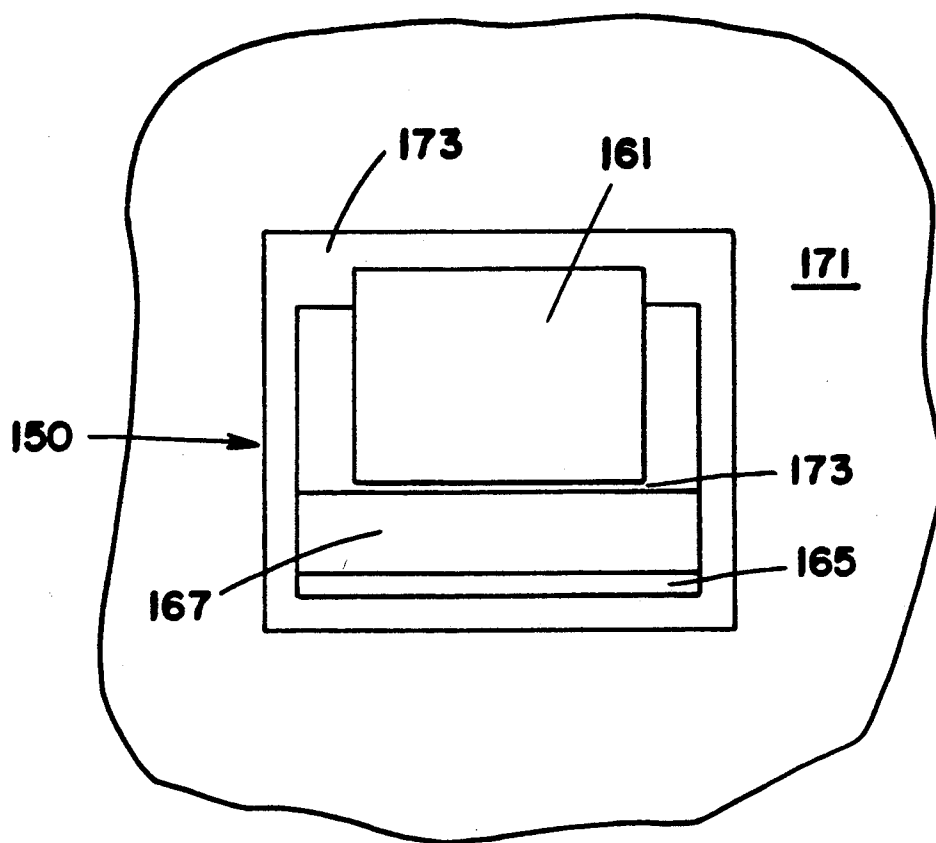
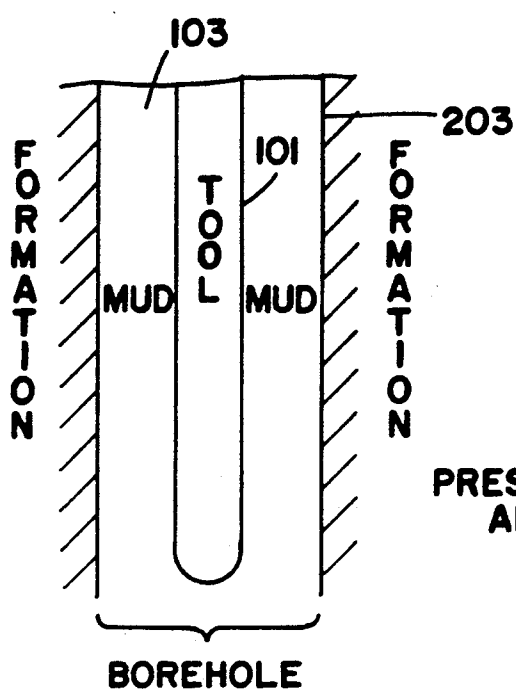
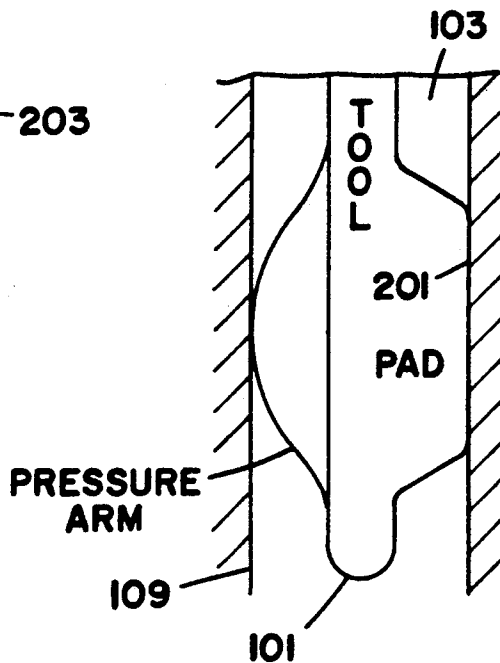


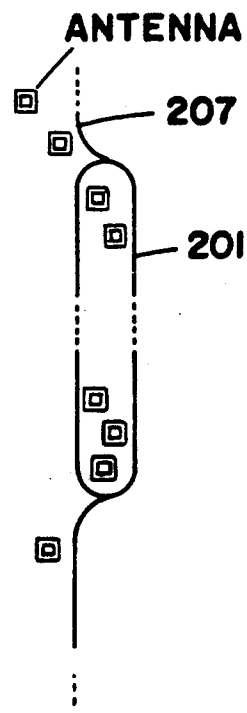
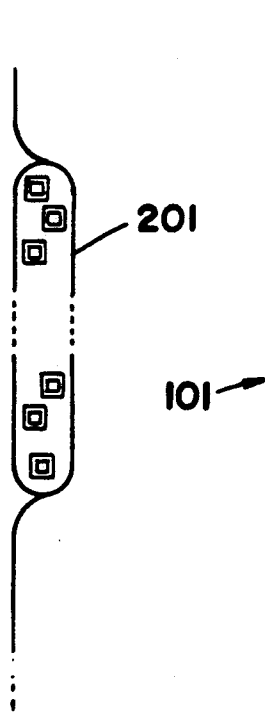
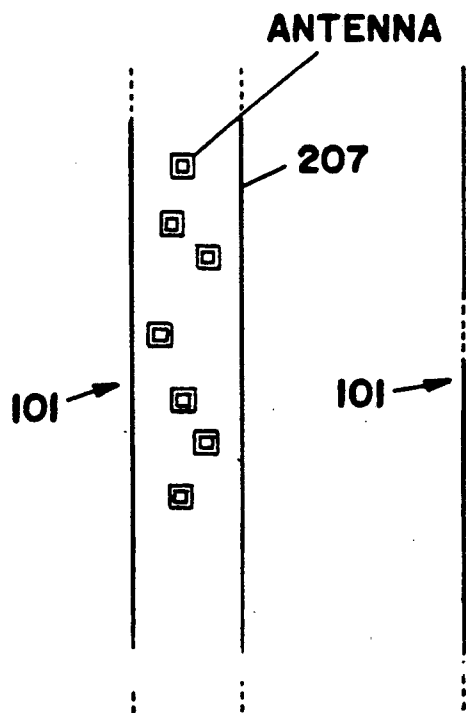
FIG _ 3



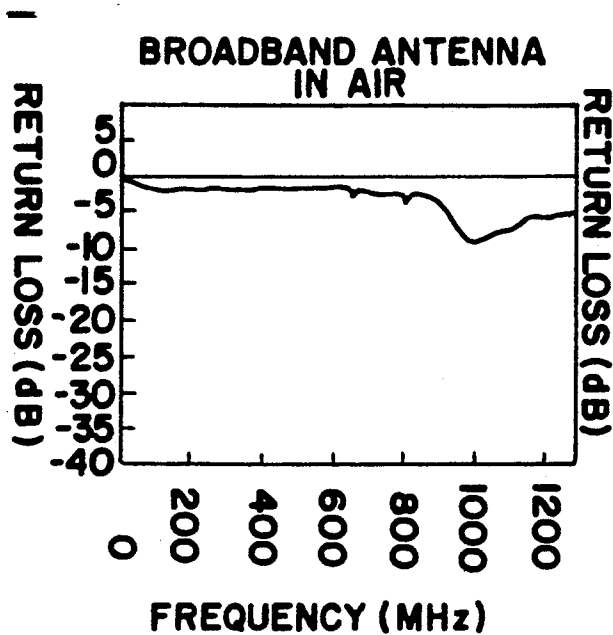
FIG_4A



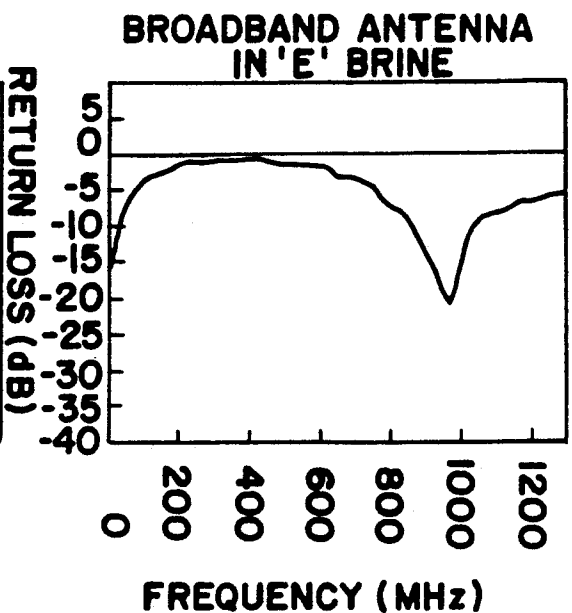
FIG_4B



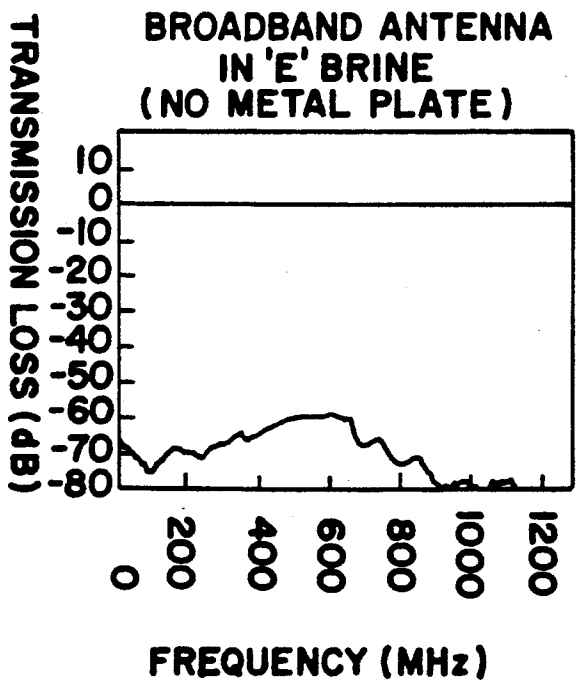
FIG_4C FIG_4D FIG_4E



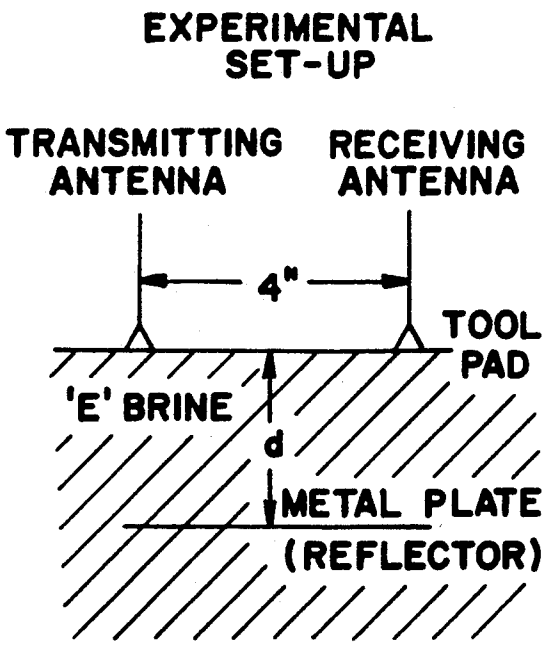
FIG_5A



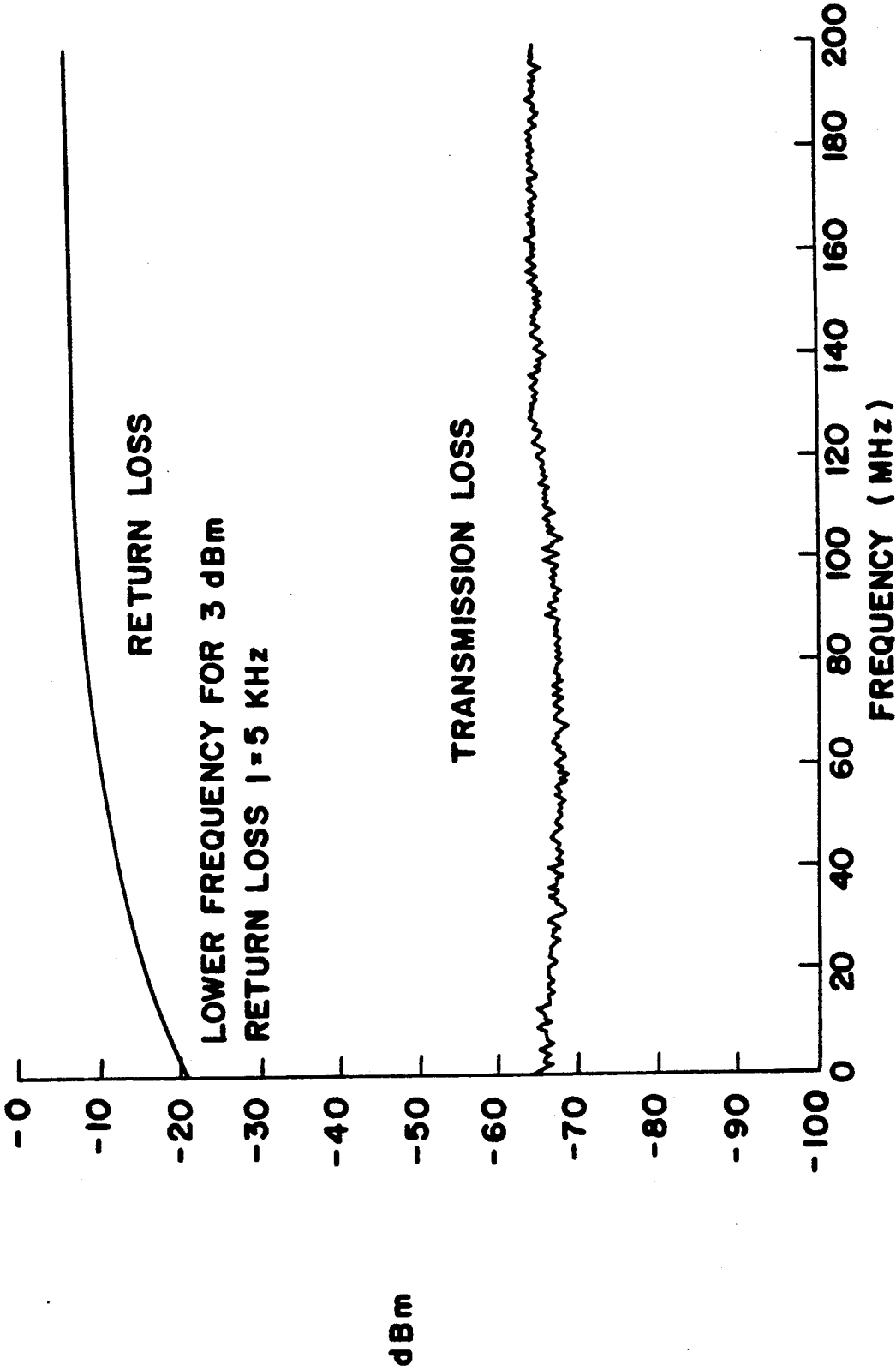
FIG_5B



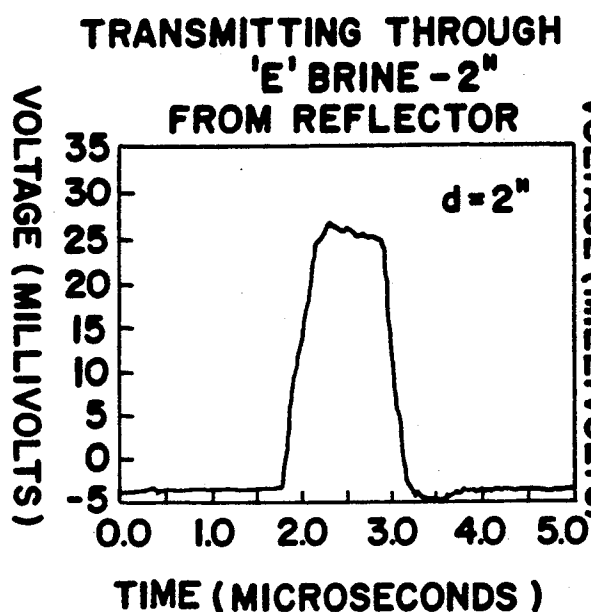
FIG_5C



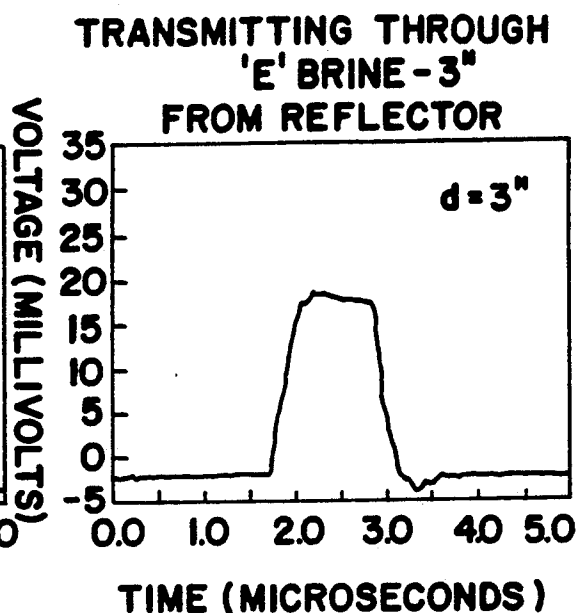
FIG_5D



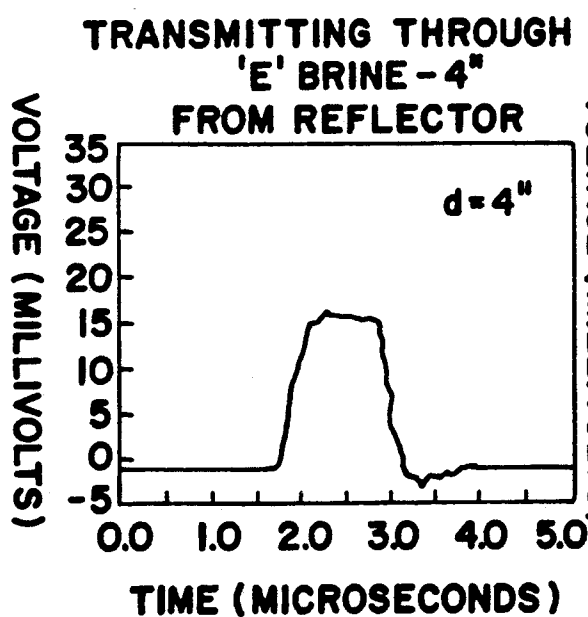
FIG_6



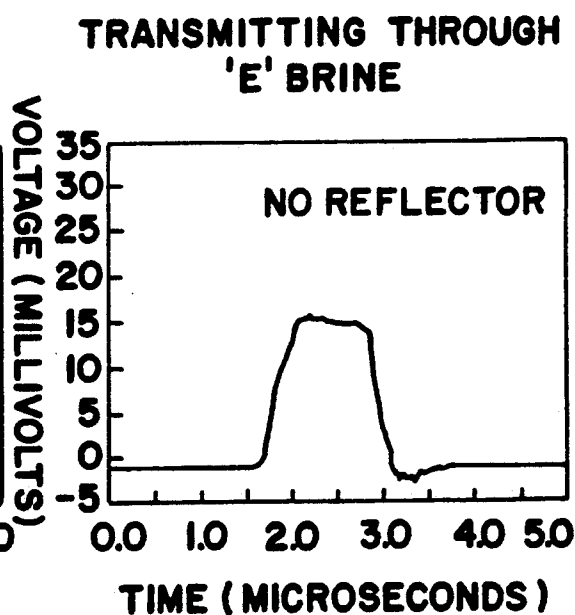
FIG_7A



FIG_7B



FIG_7C



FIG_7D

METHOD AND APPARATUS FOR BROADBAND MEASUREMENT OF DIELECTRIC PROPERTIES

FIELD OF THE INVENTION

The present invention relates generally to the analysis of materials having dissimilar dielectric properties. More specifically, this invention provides an antenna which can combine the functions of various resistivity and dielectric constant measuring devices into a single tool, capable of operating over a wide range of frequencies. It is particularly useful in the field of well logging.

BACKGROUND OF THE INVENTION

It is well known to log or record certain electrical characteristics of earth formations surrounding a well borehole as a function of depth in order to determine the location and extent of oil-bearing strata and to quantify the amount of oil present in such strata. A log of formation resistivity versus depth may indicate the presence of hydrocarbons, since hydrocarbon-bearing formations typically exhibit a higher resistivity than formations containing mostly salt water. There are only three material parameters which affect an electromagnetic wave. They are conductivity (resistivity), magnetic permeability and dielectric constant. Conductivity provides an indication of the energy absorbing characteristics of the medium, while magnetic permeability and dielectric constant give a measure of the energy storing capacity of a material. The magnetic permeability of most earth materials is the same and is equal to the magnetic permeability of free space. It is therefore of very little use in electrical logging techniques.

It is well known that conductivity or resistivity (which is the reciprocal of the conductivity) has wide variation in value for earth materials and strongly affects electromagnetic waves. A propagating electromagnetic wave has two fundamental characteristics, amplitude and phase. By comparing the amplitude and phase of an electromagnetic wave as it passes receivers, propagation characteristics due to formation may be studied. Measurement of these two characteristics (or equivalently, the wave travel time and attenuation) may be used to determine the dielectric constant and the resistivity of the media through which the wave is propagated.

Dielectric oil well logging is aimed at determining the water saturation and the water salinity in the formation from measurements of the dielectric constant and the resistivity of the formation. A number of criteria enter into the selection of the frequency of the electromagnetic wave used to probe the formation. Depending on these criteria, service companies have fielded a number of different logging tools at different frequencies. However, no one tool in the prior art is capable of probing a formation over a broad band of frequencies. It is therefore advantageous to extend the frequency range to include the function of the dielectric and the resistivity (induction) logging tools.

The objective of dielectric logging is to measure the dielectric constant and the conductivity of earth formations at a specific frequency, and deduce therefrom the water saturation and the salinity of this water. It has been found that logging at various frequency domains has various specific advantages. For example, logging at relatively high frequencies, near 1000 MHz, one probes a depth of only a few inches into the formation, so that here one measures essentially the properties of

the invaded zone (i.e., the zone where the formation fluid has been displaced by the fluid filtrate from the mud in the borehole). On the other hand, logging at relatively low frequencies, near 20 MHz, allows one to probe much deeper into the formation (~ a few feet), yielding perhaps information on the virgin formation. Logging at intermediate frequencies causes one to probe intermediate depths. The low frequency tools are of the centralized mandrel type, since at these frequencies the loss of energy in the mud annulus between the tool and the formation can be tolerated. At high frequencies, however, this loss would be prohibitive, and hence the high frequency tools must necessarily be of the pad type, where the pad directly contacts the formation or borehole wall.

The development of tools at these many different frequencies shows that it is advantageous to create a single tool capable of logging:

- (i) at a number of discrete frequencies
- (ii) over a continuous range of frequencies employing the swept frequency technique, and
- (iii) in the time-domain, resulting - upon inversion - in the same information as in (ii) above.

The main advantages of such a tool would be:

- (i) it would yield the profile of water saturation and water salinity with distance from the wellbore, and
- (ii) since a large amount of information would be gathered, this makes it possible to deduce, from the dielectric log alone, the porosity, in addition to the water saturation, and the water salinity.

U.S. Pat. No. 4,899,894, issued to Katahara et al., describes an acoustic logging tool, and does not discuss electromagnetic logging. It uses a plurality of acoustic frequencies only to accommodate a wide variety of formations having different preferred logging frequencies, and does not teach a method of broadband logging over each formation.

U.S. Pat. No. 3,982,176, issued to Meador, discloses a conventional induction log (20 KHz) and a conventional dielectric log (16 MHz) in single tool, using different antennas (coils) for the different frequencies. This is a mandrel type tool, that hangs freely in a wellbore with an annulus of mud around it. There is no mention of broadband logging.

U.S. Pat. No. 4,451,789, also issued to Meador, discloses a method of depth-probing the formation by changing the transmitter-receiver spacing. Frequency variation is not discussed. Although Meador uses three frequencies, they are very closely spaced, and are not used for the purpose of broadband logging. Meador simply uses slightly different frequencies as a way of labeling the transmitter-receiver pairs. It is therefore essentially a single frequency tool. It is also a mandrel type tool, which hangs freely in a wellbore.

U.S. Pat. No. 4,774,471, issued to Sims et al., discloses a single-frequency (between 10 MHz and 200 MHz) mandrel type tool. Sims does not discuss how their antenna can accommodate this frequency range, or whether different antennas are used for different frequencies. This patent only uses a wider range of frequencies within the operation of an earlier tool. The patent does teach that broadband dielectric logging is useful, however.

The largest hurdle to developing a broadband dielectric logging tool has been the lack of a suitable broadband antenna that can couple electromagnetic energy to

and from a formation, and that is compact enough to fit within the confines of a logging tool.

An additional advantage is that a dielectric measuring apparatus can be applied to the field of medical technology. For example, U.S. Pat. No. 4,240,445 issued to Iskander et al. teaches a method of coupling electromagnetic energy into a material such as tissue, to measure water content. Measuring lung water content is an especially useful application. However, Iskander's device is so large that only a few antennas can be placed on the chest, and the antenna cannot be described as a point source. Also, the electric field vanishes at some distance from the antenna, as the electric fields in the two parallel slots are oppositely directed. Furthermore, a resistor is included in the antenna, which dissipates much of the electromagnetic energy in the antenna itself. Additional prior work includes M. F. Iskander and C. H. Durney (1980): "Electromagnetic Techniques for Medical Diagnosis: A Review", Proceedings of IEEE, vol. 68, no. 1, and M. F. Iskander et al (1982): "Two-dimensional Technique to Calculate the EM Power Deposition Pattern in the Human Body", Journal of Microwave Power, vol. 17, no. 3.

The prior work is limited in the attempts at broadband logging (or measuring) in that no suitable single antenna element has been designed which can couple electromagnetic energy into a material, whether it be a geologic formation or tissue, over a broad range of frequencies, that is also sufficiently compact and is capable of handling high power levels. There is therefore a need for a device and a method for use in such broadband logging/measuring/heating applications.

SUMMARY OF THE INVENTION

The present invention is surprisingly successful in providing a method and apparatus for combining the functions of various resistivity and dielectric constant measuring devices and electromagnetic energy coupling device into a single tool, capable of operating over a wide range of frequencies. It is especially useful in well logging applications. The apparatus is capable of taking broadband measurements of materials having dissimilar dielectric properties.

A measuring tool such as a logging tool, having a tool face, also has a novel transmitting and a novel receiving antenna. Electromagnetic energy is transmitted to a transmitting antenna. A stripline adapter permits the energy to flow to a stripline having a metallic central strip. A strip face of the central strip is bent at approximately right angles, and has a height that is compatible with desired frequency coverage.

A ground plane extends from the stripline adapter to the right angle bend, so that a distal end of the central strip extends away from it, and a void is created between the center strip and the ground plane.

A dielectric is positioned to nearly fill the void. The dielectric is comprised of a material having a very high dielectric constant and a very low energy loss. The transmitting antenna is positioned so that the ground plane is fixedly connected to the measuring tool, and the strip face lies flush with the tool face, so that electromagnetic energy can be transmitted into the material to be analyzed.

An enclosure surrounding the stripline is comprised of four metallic walls which are positioned in electrical contact with the ground plane and the stripline adapter, so that the strip face is nearly centered in the opening created by the walls and the ground plane.

A loss-less, non-conducting material fills in any remaining open space in the enclosure, so that the non-conducting material forms an additional wall that is really flat with the strip face.

A receiving antenna is comprised in essentially the same manner as the transmitting antenna, and is positioned in the tool so that it can receive the electromagnetic energy which has traveled through the material being probed. A means for monitoring the received energy detects changes as the apparatus is moved across the material.

In another embodiment of this invention, broadband measurements are taken to determine the nature of a fluid in a material such as a geologic formation.

It is one object of this invention that electromagnetic energy is transmitted and received over a wide frequency range, specifically from 2 KHz to 1 GHz.

The tool may further comprise a pad, which conforms to the inside of a wellbore and holds the antennas. At least one transmitting and one receiving antenna are necessary. A plurality of each is often desirable. Some antennas may be staggered in a spiral fashion, to prevent undesirable coupling between adjacent antennas.

Fluids analyzed include water and hydrocarbons. Electromagnetic energy is monitored to provide an indication of the porosity, salinity, and water saturation of the material to be analyzed. Depth probing a geologic formation is a particularly useful application, to measure the nature of fluids as a function of the distance from the antennas.

The above and other embodiments, objects, advantages, and features of the invention will become more readily apparent from the following detailed description of the invention, which is provided in connection with the accompanying drawings.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic, sectional view of the inventive logging (or measuring) tool positioned in a wellbore.

FIG. 2 shows a top, front, and side view of the novel transmitting antenna.

FIG. 2A is the same view as FIG. 2, further illustrating the enclosing metallic walls.

FIG. 3 shows an antenna mounted on a tool face.

FIG. 4A-4E shows schematic side views of the inventive apparatus as applied to well logging technology.

FIG. 5A-5E show three graphs of transmission and return loss as a function of frequency.

FIG. 6 is a graph of transmission and return loss as a function of frequency, for low frequencies.

FIG. 7A-7D show four graphs of time-domain transmission measurements at various distances from a metal reflector plate in a brine.

DETAILED DESCRIPTION OF THE INVENTION

In accordance with the present invention, a new improved method and apparatus for determining the nature of various materials and the fluids contained therein, using a broadband measuring apparatus, has been developed.

Referring to the drawings, a first embodiment of the inventive broadband logging (or measuring) tool 101 is shown in FIG. 1, positioned in a wellbore 103. The wellbore wall 105 is sometimes lined with a layer of mud cake 107. Pressure arm 109 positions tool face 111 near wellbore wall 105, so that transmitting antennas

such as T_1 and T_2 and receiving antennas such as R_1 and R_2 are positioned close to the mud cake 107 or the wellbore wall 105. The transmitting antennas, such as T_n and the receiving antennas, such as R_n are mounted on the tool face 111 above and below the tool pad 119, and are positioned opposite the wallbore 105, and are separated from it by the mud cake 107 and the mud in the wellbore 103. The tool face 111 is defined as the outer surface of the logging tool 101.

A material, in this case a geologic formation 113 surrounds the wellbore. An invaded zone 115 represents the region of the formation 113 that has been permeated by the mud filtrate. The outer region 117 is that part of the formation 113 that has not been permeated by the mud filtrate. In a formation evaluation program, it is desirable to know the properties of both regions, as a function of distance from the antenna or tool face 111. This may be called depth-probing.

In FIG. 1, the logging tool 101 has a pad 119 or pad-type device so that some or all of the antennas can be positioned very close to the formation so that electromagnetic energy can be transmitted through the formation. The antennas work in pairs. That is, antennas T_1 - T_4 and T_n are transmitting antennas, and antennas R_1 - R_4 and R_n are receiving antennas. Antenna T_1 transmits electromagnetic energy through the formation, and antennas R_1 and R_2 through R_n receive it. Antenna T_2 transmits electromagnetic energy to antennas R_1 and R_2 through R_n , and so on, through antennas T_n . The antennas can all be positioned in a vertical line, as shown, or they can be staggered, in the azimuthal direction. It is possible for any given antenna to alternately play the role of a transmitting or a receiving antenna.

For any pair of antennas, $T_i R_j$, by measuring the phases and amplitudes of the received power at R_j and of the reflected power at T_i , the dielectric constant and the conductivity of the region probed by the pair $T_i R_j$ can be determined. From the dielectric constant and the conductivity, water saturation and salinity can be calculated using theoretical expressions well known in the art. It is desirable that the antennas can transmit and receive energy over the entire frequency range of interest. For dielectric well logging, a frequency range of approximately 10-1000 MHz is desirable. To include resistivity and induction logging, this range can be extended down to a few kilohertz.

The depth of investigation for a pair such as $T_3 R_3$ is a function of the frequency of the probing radiation. As this frequency is gradually reduced from a high value, the depth increases until at some frequency f_i it equals the depth d_i , roughly obtained by drawing a semicircle with $T_3 R_3$ as the diameter as seen on FIG. 1 (dashed lines). Decreasing the frequency further does not increase the depth of investigation much further. Thus, each pair $T_i R_j$ probes a zone of depth d_i appropriate to that pair and to the frequency f_i for that pair. In this way, a set of broadband antennas placed with different spacings permits information about a set of zones of varying depth to be obtained (the longer the spacing, the lower is f_i). The above discussion also illustrates that for a given transmitter-receiver pair, some depth-probing is possible, by changing the frequency. Thus, by having different transmitter-receiver spacings and the broadband capability, redundant depth-probing is possible.

Another use of the first embodiment incorporates the concept of standalone logging. In conventional dielectric logging where the dielectric constant and conduc-

tivity of a zone is measured at a single frequency, one needs an independent knowledge of the porosity of the zone in order to convert this information to water saturation and salinity. This porosity is usually derived from a separate logging tool. However, if the same zone could be probed in two very distinct frequencies, then the dual frequency data can be inverted to simultaneously calculate the porosity, water saturation and salinity, without the need of a separate logging tool.

Referring to FIG. 1 for the pair $T_4 R_4$, if the frequency is raised from f_{i+1} (which is the frequency corresponding to the maximum depth of investigation d_{i+1} for the pair), the zone of investigation will shrink from d_{i+1} until at some frequency F_{i+1} , this zone (dotted line 120) will have a depth equal d_i . Thus, having broadband antennas with different spacings permits us to probe the same depth d_i with two different frequencies.

An example of the inventive transmitting antenna 150 is shown in FIG. 2. A coaxial connecting means, such as coaxial connector 151 is electrically connected to a stripline adapter 153 which is capable of transmitting electromagnetic energy from the coaxial connector 151 to a stripline section with metallic central strip 155. An especially useful stripline adapter is a model No. 3070-1404-10 designed by Omni-Spectra, or other types of microwave stripline adapters. Other types of transmission means may be utilized to transmit electromagnetic energy to the antenna. For example, a strip transmission line may be electrically connected to the stripline section having the metallic central strip 155. As a commercial coaxial-to-stripline transition means has been utilized, the dimensions included herein reflect this means. One knowledgeable in the art would realize that the dimensions may be altered to change frequency coverage and to fine-tune performance.

Metallic center strip 155 has a front end 157, a flat strip body 159, a flat strip face 161, and a distal end 163. The front end 157 is electrically connected to the center conductor 169 of the stripline adapter 153. Solder is a particularly useful connecting means. Flat strip body 159 may also be tapered to come to a point at front end 157 to provide a smooth electrical transition between the center conductor 169 and the center strip 155. The strip face 161 is bent at approximately right angles to strip body 159, and has a height that is measured from the right angle bend to distal end 163. The height is compatible with the desired frequency coverage. The longer the height, the more lower frequency coverage is allowed. A $\frac{1}{2}$ " height permits a frequency range of approximately 2 KHz-1 GHz. The metallic center strip 155 can be made of any metal. Copper, brass, or aluminum are especially useful.

A ground plane 165 extends from stripline adapter 153 to the right angle bend in the center strip 155, so that the distal end 163 extends away from the ground plane 165 and so that a void exists between the center strip 155 and the ground plane 165. Ground plane 165 is comprised of a metal. Commercial grade stainless steel is particularly useful. It is desirable to keep the ground plane and center strip as short as possible, to permit the apparatus to remain as compact as possible and to allow the use of as many antennas as possible.

The void between the ground plane 165 and the center strip 155 is largely filled with a dielectric 167. The dielectric 167 should have a very high dielectric constant and a very low loss. By loss, we mean the dissipation of energy. The dielectric 167 can be a ceramic dielectric, and comprised of material such as Barium

Titanate or Lead Zirconate Titanate. A crystalline dielectric may also be used, although more expensive. The thickness of the dielectric 167 is determined by the stripline adapter 153 used. The dielectric 167 acts to make the capacitance of the center strip 155 very large.

The construction of the antenna is completed by enclosing the center strip 155 by metallic walls 181, 182, 183, and 184, which contact the ground plane 165 and the adapter 153 electrically, as shown in FIG. 2A. The walls add rigidity and prevent leakage of the electromagnetic radiation. The strip face 161 is approximately centered in the rectangular opening created by the edges of the walls and the edge of the ground plane 165. Thus, the distance between an edge of the strip face 161 and the adjacent edge of a wall is substantially the thickness of the dielectric 167. The entire void space in the antenna enclosed by the walls, including the set back 168 at the dielectric edge, is filled with a loss-less, non-conducting material such as a mixture of epoxy and alumina which sets hard, seals the antenna, and makes it more rugged.

The ground plane 165 and the walls 181, 182, 183, and 184 are fixedly connected to a logging (or measuring) device or tool as seen in FIG. 3. The strip face 161 is positioned to lie flush with the tool face 171 (or a tool pad), so that the transmitting antenna 150 can transmit electromagnetic energy into a material such as a geologic formation or mammal tissue. Void space 173 is filled with a loss-less, non-conducting material such as an epoxy-aluminum compound. The ground plane 165 and the walls 181, 182, and 183 connect to the tool face (or tool pad) and the center strip 161 becomes the sensor "button".

A receiving electromagnetic antenna is comprised in essentially the same manner as the transmitting antenna, and is positioned in the logging tool in the same manner as the transmitting antenna, so that the receiving antenna can receive the electromagnetic energy which has traveled through the material that is analyzed.

The logging tool also contains a means for monitoring the received electromagnetic energy for changes, as the tool is moved across the material and moves across the interface of materials having dissimilar dielectric properties so that the interface can be located, and the nature of the material can be evaluated. An example of frequently studied dielectrically dissimilar materials are hydrocarbons and water, both of which are normally contained in the pore spaces of rocks.

The logging tool is capable of transmitting and receiving electromagnetic energy that has a range of frequencies. The range of frequencies is from about 2 KHz to about 1 GHz. In this embodiment, the electromagnetic energy is of sufficient strength to travel through the material (or formation) to the receiving antenna as a propagating wave. The amplitude and the phase of the received signal contain information (dielectric constant and conductivity) about the formation. A duplicate receiving antenna is usually employed, thereby obtaining measurements that eliminate certain unknown factors. Additionally, by employing a duplicate transmitting location above or below the pair, the effects of alternate upward and downward transmission are averaged to achieve "borehole compensation", known in the art. In a second embodiment, the logging (or measuring) tool (a device) determines the nature of a fluid in a material. The material may be, for example, a geologic formation or may be a mammal tissue. In this embodiment, the device is constructed as in the first embodi-

ment, except that the means for monitoring the electromagnetic energy for changes as the apparatus is moved across the material determines the nature of the fluid. For a geologic formation, the fluids analyzed can be hydrocarbons and water.

In either the first or second embodiment, the electromagnetic energy can be monitored to provide an indication of the salinity and the water saturation of the material. If the same zone could be probed in two very distinct frequencies, then the dual frequency data can be inverted to simultaneously calculate the porosity, also.

The apparatus transmits electromagnetic pulses of designated profile shapes into the material to be analyzed, such as a geologic formation. The pulses are received by antennas spaced at different distances from the transmitter. The different receiver spacings correspond to different depths of investigation. When the received pulses are analyzed, one obtains a broadband dielectric spectrum for different depths in the formation. Together, all this information yields the depth-dependent water saturation, salinity, porosity and matrix dielectric constant (matrix identification). The depth-dependent water saturation could then be analyzed to give an estimate of the permeability. The other conventional parameters such as formation factor can also be derived from the data, if there is present in the well, a zone with 100% water saturation.

The present invention may operate either in time or frequency domain, or both. The above paragraph describes the application in the time domain. Because of the compact size of the invention, many such sensors can be installed on a tool, to comprise an array of sensors capable of "depth-probing" the formation (i.e., measuring the saturation and the salinity as a function of distance from the wellbore). The depth-probing and the wide frequency coverage aspects can possibly be combined to give the tool a stand-alone character: It can, in and of itself, determine the porosity, the salinity, and the water saturation without the need of an additional porosity tool (which is required in the present art).

FIGS. 4A-4E illustrate various applications of the inventive apparatus as applied to well logging technology. The antennas (both receiving and transmitting) can be mounted on a pad 201 or pad-type device which is designed to substantially conform to the inside of the wellbore 203, as seen in FIGS. 4B, 4D, and 4E. The pad acts to reduce or prevent propagation of the electromagnetic energy through the lossy mud 205. At low frequencies, however, the loss in the mud is tolerable and the antennas can be mounted on the tool face 207, on a centralized tool, as shown in FIGS. 4A and 4C. A combination of two arrangements is also possible, as seen in FIG. 4E, where antennas are positioned both on tool face 207 and on a pad 201 or pad-type device to include low frequency waves. The vertical spacings and azimuthal orientations are selected from theoretical considerations known in the art. Therefore, the device may comprise a single transmitting antenna and one or more receiving antennas, or it may comprise a plurality of transmitting antennas. The antennas may be oriented in several arrangements. They may be staggered about the tool face and/or pad or may be staggered in a spiral fashion. Staggering of the antennas minimizes unwanted coupling between adjacent antennas, while still permitting a short spacing distance between antennas.

It is advantageous to use several antennas at pre-selected spacings. This provides a variable depth of investigation, as one transmitting antenna could be used

with a plurality of receiving antennas. A variable frequency of investigation is also possible, as larger spacings are required with larger wavelengths. Also, redundant spacings provide enhanced quality control.

The apparatus can operate in the frequency domain, using a single frequency, multiple frequencies (such as simultaneous, selectable, or time-multiplexed for example), or swept frequency techniques. Or, the apparatus can operate in the time domain, using pulses of a wide variety of shapes, widths, rise and fall times, etc. When the pulses are transformed to the frequency domain, either electronically using a spectrum analyzer, or numerically using mathematical transforms, the same information is obtained as would be given by a frequency domain tool.

THEORY OF TIME-DOMAIN DIELECTRIC LOGGING

A time-domain tool eliminates much of the cumbersome electronics of a swept frequency or a multiple frequency tool, and shifts the burden of the electronics to software. Consider a tool with a broadband transmitting antenna located at $Z=0$ and two identical broadband receiving antennas located at Z_1 and Z_2 (Z_0 , Z_1 and Z_2 being three points along the axis of the wellbore). Suppose that an electromagnetic pulse $f(t, 0)$ of a finite duration is launched into the formation at $Z=0$ beginning at $t=0$ ($f(t, 0)=0$ for $t \leq 0$ and $t > t_0$, say).

The Fourier frequency components of this pulse are given by:

$$F(\omega, 0) = \frac{1}{2\pi} \int_0^\alpha f(t, 0) e^{i\omega t} dt \quad (1)$$

where ω is the circular frequency of the radiation. Similarly, the pulses $f(t, Z_1)$ and $f(t, Z_2)$ received at Z_1 and Z_2 can be decomposed into their spectral components:

$$F(\omega, Z_1) = \frac{1}{2\pi} \int_0^\alpha f(t, Z_1) e^{i\omega t} dt \quad (2)$$

$$F(\omega, Z_2) = \frac{1}{2\pi} \int_0^\alpha f(t, Z_2) e^{i\omega t} dt \quad (3)$$

Now, the relationship between the transmitted and received Fourier components is

$$F(\omega, Z_1) = F(\omega, 0) e^{ikZ_1} M(\omega) G(\omega, Z_1) \quad (4)$$

$$F(\omega, Z_2) = F(\omega, 0) e^{ikZ_2} M(\omega) G(\omega, Z_2) \quad (5)$$

where

$k = \alpha + i\beta$ is the complex wave number and

α = phase shift of the wave in radians/meter

β = attenuation of the wave in nepers/meter

$M(\omega)$ = factor resulting from mismatches at the transmitting antenna/formation and receiving antenna/formation interfaces

$G(\omega, Z)$ = factor resulting from geometric spread of radiation.

Dividing (5) by (4) eliminates the term $M(\omega)$, and we have

$$\frac{\alpha}{\beta} = \frac{1}{\Delta Z} \frac{G(\omega, Z_2)}{G(\omega, Z_1)} \frac{Re \left[\ln \left\{ \frac{F(\omega, Z_2)}{F(\omega, Z_1)} \right\} \right]}{Im \left[\ln \left\{ \frac{F(\omega, Z_2)}{F(\omega, Z_1)} \right\} \right]} \quad (6)$$

whence the relative dielectric constant ϵ and the conductivity σ are obtained using the relations:

$$\epsilon = \frac{\alpha^2 - \beta^2}{\epsilon_0 \mu_0 \omega^2} \quad (7)$$

$$\sigma = \frac{2\alpha\beta}{\mu_0 \omega} \text{ mho/m} \quad (8)$$

where α , β , ϵ and σ are all function of frequency.

The geometric factor in Equation (6) has to be determined experimentally by pulsing the tool in air and in other lossy media of known, lossy dielectric properties, such as brine.

In the alternative to Equation (6), the dielectric properties may also be derived by referencing to only one receiver, and using equations (4) or (5). Here, the quantity $M(\omega)$ is determined by measuring the power reflected back into the transmitting antenna due to the mismatch, as described in U.S. Pat. No. 4,831,331 issued to De and Keetch.

A prototype logging tool pad was constructed, with the inventive antennas. The pad consists of one transmitting and one receiving antenna, the distance between them being variable.

An acceptable dielectric logging antenna must meet the following criteria:

- (i) It must be able to couple sufficient energy into and from the formation at its operating frequency to allow probing of the formation;
- (ii) This probing energy must penetrate into the formation, rather than clinging to the surface of the tool pad (i.e., it must travel as a freely propagating wave rather than a surface wave guided along the pad).

In the present instance, the above two conditions must hold over the entire range of the frequency of operation.

The first of the above criteria is tested by measuring the return loss for the transmitting antenna, and the transmission loss from the transmitting to the receiving antenna - both as a function of frequency. These measurements are shown in FIG. 5 where the antenna pad is placed in air and against brine of conductivity 0.5 mho/m (to represent a formation). The return loss curve in brine shows that sufficient energy is entering the brine over the frequency range of the measuring device (Hewlett-Packard HP8505A Network Analyzer; 500 KHz - 1300 MHz) to permit probing. The transmission loss shows that sufficient energy is being received at the receiving antenna to permit measurements.

Measurements were made by using another measuring device (HP3577A Network Analyzer; 5Hz - 200 MHz) to test the low frequency limitation of the antenna. The results are shown in FIG. 6, showing that the low frequency limitation is about 5 KHz. The improved return loss performance in the 200 MHz region (at FIG. 5) results from a drying (curing) of the epoxy alumina filling between measurements.

FIG. 7 shows time-domain transmission measurements at various distances (d) to a metal reflector plate in the brine. The change in amplitude of the received

pulse as a function of the distance of the metallic reflector shows that the energy has penetrated into the brine out to the location of the plate.

While a preferred embodiment of the invention has been described and illustrated, it should be apparent that many modifications can be made thereto without departing from the spirit or scope of the invention. Accordingly, the invention is not limited by the foregoing description, but is only limited by the scope of the claims appended hereto.

What is claimed is:

1. Apparatus for making broadband measurements of materials having dissimilar dielectric properties comprising an enclosed measuring tool having a tool face, said measuring tool further comprising an electromagnetic transmitting antenna, said transmitting antenna further comprising:

- (a) a coaxial cable connecting means and means to transmit electromagnetic energy therethrough;
- (b) a stripline adapter capable of transmitting electromagnetic energy from said coaxial cable connecting means to a stripline having a metallic central strip, said center strip having a front end, a flat strip body, a flat strip face, and a distal end, said front end electrically connected to a center conductor of said stripline adapter, said strip face bent at approximately right angles to said strip body and having a height measured from said right angle bend to said distal end that is compatible with a desired frequency coverage;
- (c) a ground plane which extends from said stripline adapter to said right angle bend, so that said distal end extends away from said ground plane and so that a void exists between said center strip and said ground plane;
- (d) a dielectric largely filling said void, said dielectric comprised of a material having a very high dielectric constant and a very low energy loss, so that said transmitting antenna is positioned so that said ground plane is fixedly connected to said measuring tool and said strip face is positioned to lie flush with said tool face so that said transmitting antenna can transmit electromagnetic energy into said material;
- (e) an enclosure surrounding said stripline comprising four metallic walls, said walls positioned in electrical contact with said ground plane and said stripline adapter, so that said strip face is nearly centered in the opening created by said walls and said ground plane;
- (f) a loss-less, non-conducting material which fills in any remaining open space in said enclosure so that said non-conducting material forms an additional wall that is nearly flat with said strip face;
- (g) a receiving electromagnetic antenna comprised in essentially the same manner as said transmitting antenna, said receiving antenna positioned in said measuring tool in the same manner as said transmitting antenna, so that said receiving antenna can receive said electromagnetic energy which has traveled through said material; and
- (h) means for monitoring said received electromagnetic energy for changes as said apparatus is moved across said materials whereby said dielectric properties can be measured.

2. Apparatus as recited in claim 1 wherein said transmitting antenna transmits and said receiving antenna

receives electromagnetic energy over a frequency range of 2 KHz to 1 GHz.

3. Apparatus as recited in claim 1 further comprising a means for positioning said tool face near said material.

4. Apparatus as recited in claim 1 wherein a strip transmission line is electrically connected to said stripline, so that electromagnetic energy can be transmitted thereto.

5. Apparatus as recited in claim 1 wherein said antennas are positioned on a pad-type device.

6. Apparatus as recited in claim 1, further comprising a plurality of receiving antennas.

7. Apparatus as recited in claim 6 further comprising a plurality of transmitting antennas.

8. Apparatus as recited in claim 7 wherein said materials having dissimilar dielectric properties are hydrocarbons and water.

9. Apparatus as recited in claim 1, wherein said broadband measurements are taken to determine said dielectric properties as a function of distance from said antenna.

10. An apparatus for making broadband measurements to determine the nature of a fluid in a material, said apparatus having a tool face and further comprising a first electromagnetic transmitting antenna, said first transmitting antenna further comprising:

- (a) a coaxial cable connecting means and means to transmit electromagnetic energy therethrough;
- (b) a stripline adapter capable of transmitting electromagnetic energy from said coaxial cable connecting means to a stripline having a metallic central strip, said center strip having a front end, a flat strip body, a flat strip face, and a distal end, said front end electrically connected to a center conductor of said stripline adapter, said strip face bent at approximately right angles to said strip body and having a height measured from said right angle bend to said distal end that is compatible with a desired frequency coverage;
- (c) a ground plane which extends from said stripline adapter to said right angle bend, so that said distal end extends away from said ground plane and so that a void exists between said center strip and said ground plane;
- (d) a dielectric filling most of said void, said dielectric composed of a material having a very high dielectric constant and a very low energy loss, so that said first transmitting antenna is positioned so that said ground plane is fixedly connected to said logging tool and said strip face is positioned to lie flush with said tool face so that said first transmitting antenna can transmit electromagnetic energy into said material;
- (e) an enclosure surrounding said stripline comprising four metallic walls, said walls positioned in electrical contact with said ground plane and said stripline adapter, so that said strip face is nearly centered in the opening created by said walls and said ground plane;
- (f) a loss-less, non-conducting material which fills in any remaining open space in said enclosure so that said non-conducting material forms an additional wall that is nearly flat with said strip face;
- (g) a receiving electromagnetic antenna comprised in essentially the same manner as said transmitting antenna, said receiving antenna positioned in said apparatus in the same manner as said transmitting antenna, so that said receiving antenna can receive

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said electromagnetic energy which has traveled through said material; and

- (h) means for monitoring said electromagnetic energy for changes as said apparatus is moved across said material, so that the nature of said fluid can be determined.

11. Apparatus as recited in claim 10 wherein said transmitting antenna transmits and said receiving antenna receiver electromagnetic energy over a frequency range of 2 KHz to 1 GHz.

12. Apparatus as recited in claim 1 or 10 wherein said transmitting antenna can alternately function as a receiving antenna and said receiving antenna can alternately function as a transmitting antenna.

13. Apparatus as recited in claim 11 further comprising a pad, said pad substantially conforming to the inside of a wellbore and holding said transmitting and receiving antennas.

14. Apparatus as recited in claim 13 further comprising a plurality of receiving antennas.

15. Apparatus as recited in claim 14 further comprising a plurality of transmitting antennas.

16. Apparatus as recited in claim 15 wherein some of said antennas are positioned on said tool face and some antennas are positioned on said pad.

17. Apparatus as recited in claim 15 wherein some of said antennas are staggered.

18. Apparatus as recited in claim 15 wherein said antennas are staggered in a spiral fashion.

19. Apparatus as recited in claim 10 wherein said fluids are hydrocarbons and water.

20. Apparatus as recited in claim 1 or 10 wherein said ground plane is no greater than 10 mm in length.

21. Apparatus as recited in claim 1 or 10 wherein said strip face has a height that is no greater than 5 mm.

22. Apparatus as recited in claim 1 or 10 wherein said electromagnetic energy is monitored to provide an indication of the porosity of said material.

23. Apparatus as recited in claim 1 or 10 wherein said electromagnetic energy is monitored to provide an indication of the water saturation of said material.

24. Apparatus as recited in claim 1 or 10 wherein said electromagnetic energy is monitored to provide an indication of the salinity of said fluid.

25. Apparatus as recited in claim 1 or 10 wherein a strip transmission line is electrically connected to said stripline, so that electromagnetic energy can be transmitted thereto.

26. Apparatus as recited in claim 10 wherein said nature of said fluid is determined as a function of the distance from said antenna.

27. Method for making broadband measurements of materials having dissimilar dielectric properties comprising the steps of: forming a measuring tool having a tool face, an electromagnetic transmitting antenna and a receiving antenna, said transmitting antenna further comprising:

- (a) a coaxial cable connecting means and means to transmit electromagnetic energy therethrough;
- (b) a stripline adapter capable of transmitting electromagnetic energy from said coaxial cable connecting means to a stripline having a metallic central strip, said center strip having a front end, a flat strip body, a flat strip face, and a distal end, said front end electrically connected to a center conductor of said stripline adapter, said strip face bent at approximately right angles to said strip body and having a height measured from said right angle bend to said

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distal end that is compatible with a desired frequency coverage;

- (c) a ground plane which extends from said stripline adapter to said right angle bend, so that said distal end extends away from said ground plane and so that a void exists between said center strip and said ground plane;

- (d) a dielectric largely filling said void, said dielectric comprised of a material having a very high dielectric constant and a very low energy loss, so that said transmitting antenna is positioned so that said ground plane is fixedly connected to said measuring tool and said strip face is positioned to lie flush with said tool face so that said transmitting antenna can transmit electromagnetic energy into said material;

- (e) an enclosure surrounding said stripline comprising four metallic walls, said walls positioned in electrical contact with said ground plane and said stripline adapter, so that said strip face is nearly centered in the opening created by said walls and said ground plane;

- (f) a loss-less, non-conducting material which fills in any remaining open space in said enclosure so that said non-conducting material forms an additional wall that is nearly flat with said strip face;

- (g) said receiving antenna comprised in essentially the same manner as said transmitting antenna, and positioned in said measuring tool in the same manner as said transmitting antenna, so that said receiving antenna receives said electromagnetic energy which has traveled through said material;

interconnecting said measuring tool with a means for monitoring said electromagnetic energy for changes as said measuring tool is moved across said materials whereby said dielectric properties can be measured; interconnecting said measuring tool with a source of electromagnetic energy; and moving said measuring tool across said materials.

28. Method as recited in claim 27 wherein said transmitting antenna transmits and said receiving antenna receives electromagnetic energy over a frequency range of 2 KHz to 1 GHz.

29. Method as recited in claim 27 further comprising a means for positioning said tool face near said material.

30. Method as recited in claim 27 wherein a strip transmission line is electrically connected to said stripline, so that electromagnetic energy can be transmitted thereto.

31. Method as recited in claim 27 wherein said antennas are positioned on a pad-type device.

32. Apparatus as recited in claim 27 further comprising a plurality of receiving antennas.

33. Apparatus as recited in claim 32 further comprising a plurality of transmitting antennas.

34. Apparatus as recited in claim 27 wherein said materials having dissimilar dielectric properties are hydrocarbons and water.

35. Method as recited in claim 27 wherein said broadband measurements are taken to determine said dielectric properties as a function of distance from said antenna.

36. Method for making broadband measurements to determine the nature of a fluid in a material, comprising the steps of: forming an apparatus having a tool face, an electromagnetic transmitting antenna, and a receiving antenna, said transmitting antenna further comprising:

- (a) a coaxial cable connecting means and means to transmit electromagnetic energy therethrough;
 - (b) a stripline adapter capable of transmitting electromagnetic energy from said coaxial cable connecting means to a stripline having a metallic central strip, said center strip having a front end, a flat strip body, a flat strip face, and a distal end, said front end electrically connected to a center conductor of said stripline adapter, said strip face bent at approximately right angles to said strip body and having a height measured from said right angle bend to said distal end that is compatible with a desired frequency coverage;
 - (c) a ground plane which extends from said stripline adapter to said right angle bend, so that said distal end extends away from said ground plane and so that a void exists between said center strip and said ground plane;
 - (d) a dielectric largely filling said void, said dielectric comprised of a material having a very high dielectric constant and a very low energy loss, so that said transmitting antenna is positioned so that said ground plane is fixedly connected to said measuring tool and said strip face is positioned to lie flush with said tool face so that said transmitting antenna can transmit electromagnetic energy into said material;
 - (e) an enclosure surrounding said stripline comprising four metallic walls, said walls positioned in electrical contact with said ground plane and said stripline adapter, so that said strip face is nearly centered in the opening created by said walls and said ground plane;
 - (f) a loss-less, non-conducting material which fills in any remaining open space in said enclosure so that said non-conducting material forms an additional wall that is nearly flat with said strip face;
 - (g) said receiving antenna comprised in essentially the same manner as said transmitting antenna, and positioned in said apparatus in the same manner as said transmitting antenna, so that said receiving antenna receives said electromagnetic energy which has traveled through said material;
- interconnecting said measuring tool with a means for monitoring said electromagnetic energy for changes as said apparatus is moved across said material whereby said nature of said fluid can be determined;

interconnecting said apparatus with a source of electromagnetic energy; and moving said apparatus across said material.

37. Method as recited in claim 36 wherein said transmitting antenna transmits and said receiving antenna receiver electromagnetic energy over a frequency range of 2 KHz to 1 GHz.

38. Method as recited in claim 27 or 36 wherein said transmitting antenna can alternately function as a receiving antenna and said receiving antenna can alternately function as a transmitting antenna.

39. Method as recited in claim 37 further comprising a pad, said pad substantially conforming to the inside of a wellbore and holding said transmitting and receiving antennas.

40. Method as recited in claim 39 further comprising a plurality of receiving antennas.

41. Method as recited in claim 40 further comprising a plurality of transmitting antennas.

42. Method as recited in claim 41 wherein some of said antennas are positioned on said tool face and some antennas are positioned on said pad.

43. Method as recited in claim 40 wherein said antennas are staggered in a spiral fashion.

44. Method as recited in claim 37 wherein said fluids are hydrocarbons and water.

45. Method as recited in claim 27 or 36 wherein said ground plane is no greater than 10 mm in length.

46. Method as recited in claim 27 or 36 wherein said strip face has a height that is no greater than 5 mm.

47. Method as recited in claim 27 or 36 wherein said electromagnetic energy is monitored to provide an indication of the porosity of said formation.

48. Method as recited in claim 27 or 36 wherein said electromagnetic energy is monitored to provide an indication of the water saturation of said formation.

49. Method as recited in claim 27 or 36 wherein said electromagnetic energy is monitored to provide an indication of the salinity of said formation.

50. Method as recited in claim 27 or 36 wherein a strip transmission line is electrically connected to said stripline, so that electromagnetic energy can be transmitted thereto.

51. Method as recited in claim 36 wherein said nature of said fluid is determined as a function of the distance from said antenna.

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[54] MICROWAVE SYSTEM FOR MONITORING WATER CONTENT IN A PETROLEUM PIPELINE

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[51] Int. Cl.⁴ G01N 22/00

[52] U.S. Cl. 324/640; 73/61.1 R; 73/73; 324/637

[58] Field of Search 324/58 A, 58.5 A, 58 R, 324/58.5 R, 58 C, 58.5 C; 73/61.1 R, 73, 64

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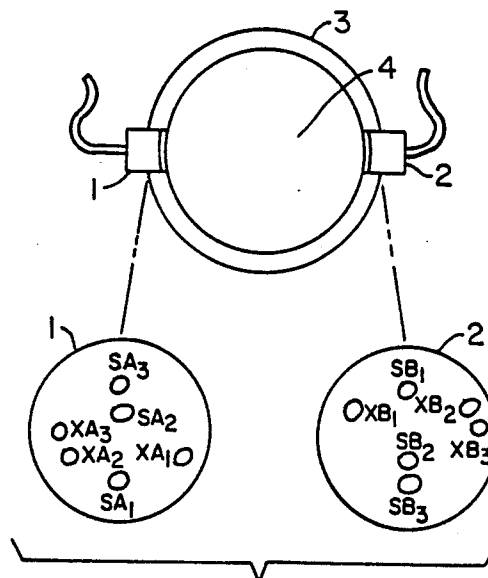
Assistant Examiner—Robert W. Mueller

Attorney, Agent, or Firm—Edward J. Keeling

[57] ABSTRACT

A method and apparatus for determining the water content of crude oil in a pipeline is disclosed. The device consists of S-band transmitting and receiving antennas, and X-band transmitting and receiving antennas. These are used to determine the complex dielectric constant of the fluid in a pipeline. Water salinity and an adjustment to the mixing formula are calculated using X-band and S-band sidewall links. The overall water content of the pipeline can then be determined by using as S-band main link that transmits a wave through a representative portion of the entire pipeline.

12 Claims, 1 Drawing Sheet



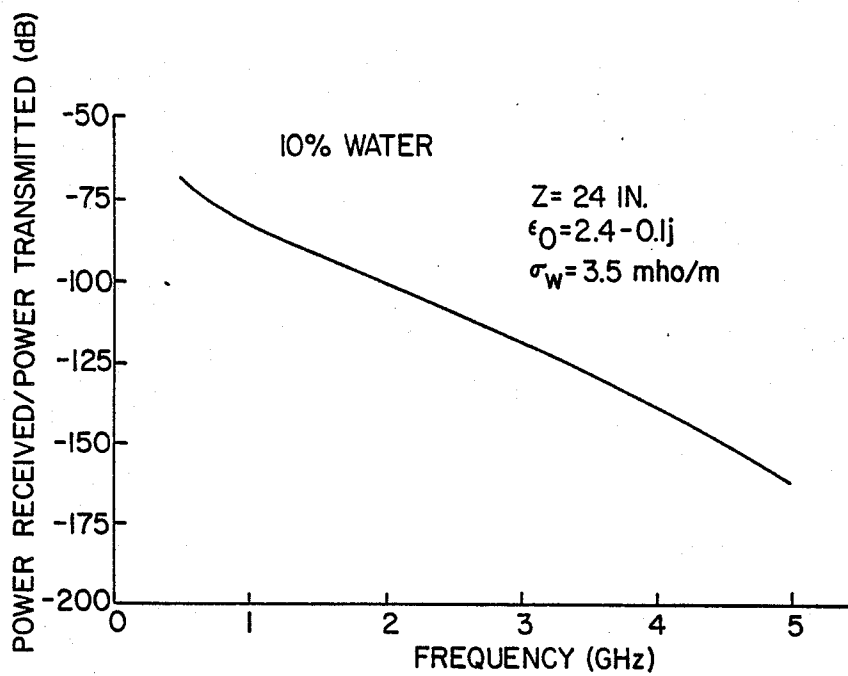


FIG. 1.

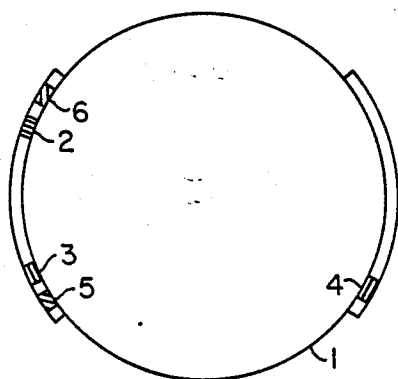


FIG. 2.

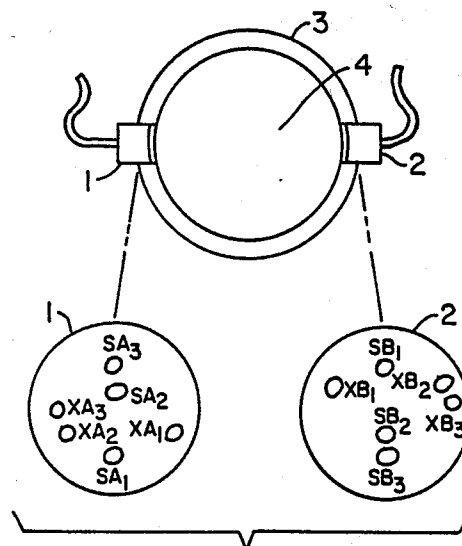


FIG. 3.

MICROWAVE SYSTEM FOR MONITORING WATER CONTENT IN A PETROLEUM PIPELINE

FIELD OF THE INVENTION

The present invention relates to the field of two-phase measurement. More specifically, the present invention relates to measurement of the water content of petroleum in a petroleum pipeline. It can also be applied to multi-phase measurement of other material.

BACKGROUND OF THE INVENTION

Crude oil produced from subterranean wells is frequently contaminated with undesirable materials. The most common of these materials is water. The fluid produced from an oil well can contain anywhere from less than 1% water to 99% water or more. Produced fluids containing these high "water cuts" are treated to remove most or all of the water because crude oil sales contracts typically allow a maximum of 1 to 3% water.

After treatment, the crude oil stream is monitored to determine the amount of water remaining in the crude. Various methods of monitoring the water content of a crude oil stream have been proposed. For example, U.S. Pat. No. 4,596,136 describes a system in which a sample of oil is removed. This system (and all others which require the removal of a sample) assume that the water content of the sample is representative of the water content of the entire flow stream. This is frequently not a valid assumption, particularly in large pipelines which contain significant concentrations of water.

Other methods have also been proposed. For example, spinners, venturies, or capacitance probes have been used to determine the water content of crude oil. Among other disadvantages, all of these systems require the insertion of one or more devices into the crude oil stream. These intrusive systems can significantly increase the pressure drop in a pipeline, requiring additional pumping capacity. Many of these devices also assume that the conditions in one portion of the pipeline are representative of the entire pipeline. This again may not be the case.

In summary, there is a need to provide a method and means for determining the water content of flowing crude oil streams which is highly accurate, nonintrusive, and which does not require the removal of a sample that is representative of the entire crude oil stream.

BRIEF SUMMARY OF THE INVENTION

The present invention provides a nonintrusive method and means for accurately determining the water content of crude oil flowing in a pipeline. The device is comprised of two antenna pots mounted flush in the walls of a petroleum pipeline. In each of the ports are various S- and X-band antennas. These antennas are used to derive the real and imaginary parts of the complex dielectric constant of the oil/water mix (ϵ^*) from which the volume fraction of water (ϕ) can ultimately be determined.

In the first port is an S-band (or other low frequency) transmitting antenna and in the second port is an S-band receiving antenna. Since an ideal mixing formula for the complex dielectric constant in the low frequency region is not known, the volume fraction of water cannot be calculated directly. Therefore, an "adjustment factor" (ρ) must be calculated. In addition, it is necessary to

know the conductivity of the water (σ_w) to calculate ϕ when ϵ^* is known.

The adjustment factor and water conductivity are determined by utilizing a set of low frequency (S-band) and (X-band) transmitting and receiving antennas contained entirely within one of the antenna ports. Across the short distance of the antenna port, the attenuation and the phase shift of a transmitted signal in either the X- or S-band can be determined unambiguously. From the measurements, the value of ϵ_s^* and ϵ_x^* , i.e., the value of ϵ^* in the S- and X-band for the mixture near the wall, are determined. Using ϵ_x^* , the value of σ_w and the volume content of water near the wall (ϕ) can also be determined since no adjustment factor to the mixing formula is necessary for X-band radiation. By knowing σ_w and ϕ , the value of the S-band adjustment factor to the mixing law (ρ) can be calculated for the near-wall region. Since the S-band adjustment factor to the mixing formula determined at any given time and the dielectric constant of water can be assumed to be constant throughout the volume of the pipe, these values of ρ and σ_w can also be applied to the S-band link across the pipe. While it is not possible to unambiguously measure the phase shift in the S-band link across the pipe, it is possible to calculate it if the distance between the S-band antennas in the wall, and the two ports is known.

The wave attenuation in the S-band link across the pipe is then measured, making it possible to determine the overall volume fraction of water contained within the pipe (ϕ) in the region between the antenna ports.

The apparatus for carrying out the above calculations consists of a first antenna port mounted flush in a wall of the pipeline, the first antenna port contains an X-band link and a sidewall S-band link. The X-band link consists of an X-band transmitting antenna and an X-band receiving antenna located within one-half of the minimum expected effective wavelength of the X-band radiation. The sidewall S-band link consists of a sidewall S-band transmitting antenna and a sidewall S-band receiving antenna located likewise within one-half of the wavelength of the S-band radiation. A main link S-band transmitting antenna is also included in the first antenna port.

A second antenna port is mounted flush in the wall of the pipeline substantially diametrically opposite the first antenna port. The second antenna port contains a main link S-band receiving antenna. The device also includes a means for generating waves, a means for measuring phase shift, and attenuation of a signal transmitted through the X-band link, a means for measuring phase shift and attenuation of a signal transmitted through said sidewall S-band link, and a means for measuring attenuation of a signal transmitted from the main link S-band transmitting antenna to the main link S-band receiving antenna.

Duplicates of the above antennas may be provided to increase the accuracy of the device. For example, the sidewall X-band link may comprise an X-band transmitting antenna and two X-band receiving antennas. Similarly, the S-band links may comprise a single transmitting and two receiving antennas. Further, the second antenna port may be similarly arranged to the first antenna port. When the first antenna port transmits in the S-band link, the second antenna port receives and vice versa. It is also possible to provide two sets of the antenna ports along horizontal and vertical diameters of the pipe to detect and quantify gravitational settling.

Unlike the prior art, in utilizing the above approach it is not necessary to assume that the overall water content of the oil in the pipe is represented by an individual portion of the pipe since a bulk volume fraction water will be found. Further, it is unnecessary to insert a device into the flowing stream of oil which would not only increase the pressure drop in the pipeline, but can also result in disturbances to the flow stream at the point of measurement that will result in measurement inaccuracies.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows the ratio of power received to power transmitted for various frequency signals.

FIG. 2 illustrates schematically the manner in which the described invention is operated.

FIG. 3 shows the anticipated antenna configuration in the preferred embodiment. The antenna ports are shown in the pipeline in cross-section and in enlarged front views.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the discussion below it is not necessary to assume that the distribution of water over a cross section of a pipeline is uniform. It is, however, necessary to assume that the distribution of water conductivity is uniform over the cross section of the pipeline. In almost all cases this will be a valid assumption. It is also necessary to assume that the adjustment to the mixing formula for high frequency radiation is the same near the wall as it is throughout the pipe. This will generally be a valid assumption if the *shape* of the water droplets is substantially the same throughout the pipe because droplet shape largely determines ρ .

By transmitting electromagnetic waves some distance through a fluid medium (flowing or not), it is well known that two parameters of the medium may be measured:

α =phase shift of the wave (radians/meter)

β =attenuation of the wave (neper/meter)

From these two parameters it is also well known that the real and imaginary parts of the complex dielectric constant (ϵ^*) can be described as follows:

$$\epsilon^* = \epsilon' - i\epsilon'' \quad (1)$$

$$\epsilon' = \frac{\alpha^2 - \beta^2}{\mu\omega^2} \quad (2)$$

$$\epsilon'' = \frac{2\alpha\beta}{\mu\omega^2} \quad (3)$$

where:

ϵ' =the real part of the complex dielectric constant
 ϵ'' =the imaginary part of the complex dielectric constant

μ =permeability of free space

ω =the circular frequency of the wave ($=2\pi f$ where f =the frequency of the wave)

i =the imaginary constant ($=\sqrt{-1}$)

When the medium is a two-phase mixture of oil and water, it is useful to find a "mixing formula" that will relate the dielectric constant of oil (ϵ_o^*), the dielectric constant of water (ϵ_w^*), and the dielectric constant of the mixture (ϵ^*) to the volume fraction of water (ϕ). For higher frequency waves (X-band) the mixing law can be defined as follows:

$$\epsilon_x^* = [(1-\phi)\epsilon_o^{*1/2} + \phi\epsilon_w^{*1/2}]^2 \quad (4)$$

(where the subscript "o" indicates oil, the subscript "w" indicates water, and the subscript "x" indicates the composite dielectric constant for X-band radiation).

For lower frequency waves it is necessary to provide a "correction factor" (ρ) to the above equation in order to account for the manner in which the oil is disseminated in the oil (e.g., fine mist, oval shaped drops, streaks, etc.). Although this correction factor could be applied in any of several ways to the above equation, in the preferred embodiment the mixing law for S-band radiation is described as follows:

$$\epsilon_s^* = [(1-\phi)\epsilon_o^{*1/2} + \phi\epsilon_w^{*1/2}\rho] \quad (5)$$

(where the subscript "s" indicates the composite dielectric constant for S-band radiation).

It is also known that the dielectric constants for oil and water can be described by the following equations:

$$\epsilon_o^* = a - ib \quad (6)$$

$$\epsilon_w^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (i\omega\tau)^{1-\nu}} - \frac{i\sigma_w}{\omega} \quad (7)$$

where:

a =real part of the complex dielectric constant for oil
 b =imaginary part of the complex dielectric constant for oil

σ_w =water conductivity

ϵ_∞ =dielectric constant for water at infinitely high frequency

$\epsilon_s = C - DT + ET^2$

T =fluid temperature

C, D, E =Constants (See later discussion)

τ =a time constant related to the dielectric absorption feature for water

ν =a well known constant (see Shawn et al., *J. Chem. Physics*, vol. 67, p. 2257)

It is desirable to rely on the highest possible frequency radiation in using the device for the following reasons. First, at low frequencies antenna dimensions would become impractically large in relation to the size of a pipeline. Second, at low frequencies unwanted interactions of the radiation with the metallic walls of the pipe set in and, third, at higher frequencies the mixing formula is relatively easily defined, [e.g., by equation (5) above].

The upper bound of the frequency is limited by the power ratio which can be practically measured. With a high quality preamplifier, the minimum detectable power level at the receiving antenna would be 80 decibels below one milliwatt (dBm). A realistic value of the transmitted power is 10 watts or 40 dBm. Thus, the minimum power ratio is:

$$40 \text{ dBm} - (-80 \text{ dBm}) = 120 \text{ dBm}$$

The ratio of power received (P_r) to power transmitted (P_t) is:

$$\frac{P_r}{P_t} = \frac{T_c^2 G^2 \lambda^2}{16\pi^2 Z^2} e^{-2\beta Z}$$

where:

Z =the distance between transmitting and receiving points

T_c =the power transmission coefficient at the antenna/fluid interface

G =the gain of the transmitting or receiving antenna (assumed to be identical)

λ =the effective wavelength in the fluid

FIG. 1 illustrates the minimum power ratio versus frequency for a typical petroleum pipeline by plotting the quantity $10 \log (P_r/P_t)$ as a function of frequency when:

Power loss due to antenna/fluid mismatch = -3 dB

Antenna gain = 0 dB

Pipeline diameter = 24 inches

$\epsilon_o = 2.4 - i 0.1$

$\sigma_w = 3.5 \text{ mho/m}$

From this graph it can be found that in a typical application, the maximum frequency which can be employed is 3 GHz.

It should be noted, however, that at this frequency it is impossible to (1) measure α across the pipe because this value can only be measured unambiguously when the pipeline diameter is one-half the effective wavelength or less, and (2) measure ϕ because at this frequency it is necessary to apply an unknown correction factor ρ to the mixing equation.

In order to overcome the above difficulties, the following device/method is employed as schematically illustrated in FIG. 2 (not drawn to scale for illustration purposes).

Two S-band links are installed in a pipeline 1. The first consists of an S-band transmitting antenna 2 and S-band receiving antennas 3 and 7 (the S-band sidewall link) and the second consists of an S-band transmitting antenna 2 and S-band receiving antenna 4 (the S-band main link). The antennas are mounted flush with the pipeline wall in nonmetallic, preferably ceramic, windows. The main link antennas are placed in the pipeline such that a wave passed through the main link will pass through a representative portion of the two-phase fluid contained within it. In addition, an X-band sidewall link consisting of an X-band transmitting antenna 5 and an X-band receiving antenna 6 is installed flush with the pipeline walls.

Initially, S-band transmitting antenna 2 transmits a signal to S-band receiving antenna 3 and X-band transmitting antenna 5 transmits a signal to X-band receiving antenna 6. The phase shift α and attenuation β of both of these waves can be readily and unambiguously determined because of the short distance involved and, therefore, the values of ϵ_s^* and ϵ_x^* can be calculated from equations (1), (2), and (3) above. Values of a , b , ϵ_∞ , C , D , E , τ , ν , and T can also be readily determined as follows:

C , D , and E are empirical constants which can be found in R. P. Wharton et al. doc. of Petroleum Engineers, Paper 9267 (1981).

T can be measured continuously in the pipeline with a temperature probe;

ϵ_∞ can be readily located in standard tables (≈ 4.6);

a and b can be measured in the laboratory or derived from reference tables (since these values will vary only slightly with time and will also vary only slightly from one crude oil to the next). Note that these values are also frequency independent;

τ can also be derived from standard reference tables; and

ν can be determined from standard reference tables, and in any case can be assumed to be very small or approaching 0 (greatly simplifying the calculations). It is assumed here to be 0.014.

With knowledge of these variables, as well as the frequency of the X-band and S-band waves, it is possible to simultaneously solve equations (4) and (5) for σ_w , ρ , and ϕ by substituting equations (6) and (7) in for ϵ_o and ϵ_w respectively. Note that it is possible to solve these two equations simultaneously to obtain 3 values because ϵ_s^* and ϵ_x^* are complex values.

The S-band transmitting antenna 2 now transmits a signal to S-band receiving antenna 4. The phase shift α of this signal cannot be determined unambiguously but can be calculated. First, a trial value of the phase shift, α_o , is calculated by multiplying the phase shift in the sidewall link by the ratio:

$$\alpha_o = \frac{\text{Distance from antenna 2 to antenna 6}}{\text{Distance from antenna 2 to antenna 3}}$$

We then add 180° of phase as many times as needed to the measured phase shift α to bring the result closest to α_o . This will give the correct value of the main links phase shift (except in the event that the average water saturation is drastically different from the near wall saturation).

The attenuation β of this signal can be easily measured and, therefore, the value of ϵ_s^* can be calculated across the pipeline with equations (1), (2) and (3). Furthermore, the value of ρ for the sidewall links should be approximately the same as for the main link for the reasons discussed above. Also, as stated above, it is assumed that the conductivity of the water is uniform throughout the pipeline and is assumed to be constant. Therefore, the spatially-averaged water fraction ϕ across the pipeline can be determined from equation (5).

As stated above, FIG. 2 is a simplified drawing intended to illustrate the operation of the system. The actual antenna configuration of the preferred embodiment is shown in FIG. 3. In the preferred embodiment, multiple transmitting and receiving antennas are provided in both the sidewall and main links. In addition, the first antenna port is duplicated in the second antenna port. This allows accuracy improvement through making sidewall measurements near both the ports and averaging of their values. In addition, if the values differ radically, it will be an indication of asymmetric distribution in the liquid mixture composition.

The device consists of a first antenna port 1 and a second antenna port 2 mounted flush in the sidewall of a pipeline 3 through which a gas-free oil/water mixture 4 is flowing. The first S-band main link transmitter is a two-element array of antennas designated SA₁ and SA₂. Similarly, the first S-band main link receiver is a two-element array of antennas designated SB₁ and SB₂. This configuration is used to create narrow, focused beams at transmission and to concentrate energy on the receiving antennas, which are likewise focused in the direction of the transmitting antennas. The power thus received at the second antenna port is compared with the power received at the first antenna port with the antenna designated SA₃. By doing so, the effect of mismatch at the antenna/fluid interface is eliminated and we obtain the absolute power loss for the path length that is the difference between the main link path length and the path length from the transmitting antennas SA₁, and SA₂ to receiving antenna SA₃.

Redundant measurements can be made by reversing the role of the antenna ports, i.e., by using SB₁ and SB₂ as transmitting antennas and SA₁ and SA₂ as receiving antennas, with SB₃ used to eliminate mismatch at the antenna/fluid interface.

The S-band sidewall links consists of antenna SA₁ as the transmitter and SA₂ and SA₃ as the receivers. The power from SA₁ is sequentially received by SA₂ and SA₃, which are spaced at a distance less than one-half of the effective wavelength apart. Upon taking the difference of the two measurements, α and β can be determined and hence ϵ' and ϵ'' for the sidewall region (which in a typical case will be about one inch from the wall). Duplicate measurements are made to obtain greater accuracy by using SB₁ as a transmitting antenna and SB₂ and SB₃ as receiving antennas.

Similarly, the X-band sidewall links consists of antenna XA₁, used as a transmitting antenna, and XA₂ and XA₃ used as receiving antennas. Upon taking the ratio of the two measurements, α and β can be determined and, hence, ϵ' and ϵ'' . Again, duplicate measurements are made for accuracy in the opposite sidewall by using XB₁ as a transmitting antenna and XB₂ and XB₃ as receiving antennas.

All of the above-mentioned attenuation measurements will need to be corrected for an inherent attenuation due to well known "geometric spreading" of radiation (also known as space loss). This correction factor can be calculated from theoretical considerations well known to one skilled in the art or may be determined for all fluids in the system in the laboratory with fluids of known dielectric properties such as alcohol and brines.

From the X-band measurements of ϵ' and ϵ'' , we can readily obtain the values of ϕ and σ_w for the near wall region using equations (1) to (4) and (7). Using these two values and the values of ϵ' and ϵ'' obtained from the S-band sidewall link, we can calculate the value of (ρ) from equation (5). Knowledge of these values allows calculation of the water fraction across the cross section of pipe.

All of the antennas discussed above are circularly polarized to minimize the effects of stray radiation.

It should be noted that the above system could be fully automated and computerized so as to provide a continuous measurement of the water fraction ϕ . This would also allow all measurements to be taken in a time period short enough that the water content does not change during the measurement. It should also be noted that by calculating the conductivity of the water that the salinity of the water can also be continuously monitored.

It is to be understood that while the invention has been described above with a great deal of particularity, that it is manifest that many details of construction and the arrangement of the components may be possible without departing from the spirit and scope of the invention.

For example, the above-described device could be used to measure the composition of materials other than water and oil. Further, with a simple extension of the above-described calculations, the device could be used for three or four-phase measurement. Still further, while the invention has been described with reference to X-band and S-band radiation, other frequencies may be optimum for various pipeline sizes and fluid types. Therefore, the invention is not to be limited by the embodiment set forth herein but is to be limited instead

by the attached claims, including the full range of equivalency to which each is entitled.

What is claimed is:

1. Apparatus for analyzing a multi-phase liquid comprising:

pipeline means for containing the liquid;
a low frequency transmitting antenna substantially in the S-band near a wall of said means for containing a liquid;

a low frequency receiving antenna substantially in the S-band located within one-half wavelength of said low frequency transmitting antenna;

means for determining a phase shift of a low frequency wave; and

means for determining an amplitude change of the low frequency wave.

2. Apparatus as recited in claim 1 further comprising:

a complementary high frequency transmitting antenna substantially in the X-band located substantially near said low frequency transmitting antenna;

a first high frequency receiving antenna substantially in the X-band located within one-half wavelength of said high frequency transmitting antenna;

a second high frequency receiving antenna substantially in the X-band located such that a wave transmitted from said high frequency transmitting antenna to said second high frequency receiving antenna passes through a representative portion of the liquid;

means for determining a phase shift and an amplitude change of a wave transmitted from said high frequency transmitting antenna and said first high frequency receiving antenna; and

means for determining an amplitude change of a wave transmitted from said high frequency transmitting antenna to said second high frequency receiving antenna.

3. Apparatus as recited in claim 2 wherein said means for containing a liquid is a petroleum pipeline.

4. Apparatus as recited in claim 3 wherein said antennas are located in ceramic windows flush with the walls of said pipeline.

5. Apparatus as recited in claim 4 further comprising:

a duplicate first high frequency receiving antenna substantially in the X-band located adjacent said first high frequency receiving antenna;

a duplicate second high frequency receiving antenna substantially in the X-band located adjacent said second high frequency receiving antenna; and

a duplicate low frequency receiving antenna substantially in the X-band located adjacent said low frequency receiving antenna.

6. Apparatus for determining the water content of crude oil in a pipeline comprising:

(A) a first antenna port mounted flush in a wall of the pipeline further comprising:

(1) an X-band link comprising:

(a) an X-band transmitting antenna;

(b) an X-band receiving antenna located with one-half the wavelength of said X-band transmitting antenna;

(2) a sidewall S-band link comprising:

(a) a sidewall S-band transmitting antenna;

(b) a sidewall S-band receiving antenna located with one-half wavelength of said first S-band transmitting antenna;

(3) a main link S-band transmitting antenna;

- (B) a second antenna port mounted flush in the wall of the pipeline, said second antenna port containing a main link S-band receiving antenna;
- (C) means for measuring phase shift and attenuation of a signal transmitted through said X-band link; 5
- (D) means for measuring phase shift and attenuation of a signal transmitted through said sidewall S-band link; and
- (E) means for measuring attenuation of a signal transmitted from said main link S-band transmitting antenna to said main link S-band receiving antenna. 10
7. Apparatus as recited in claim 6 further comprising:
- (a) a duplicate X-band receiving antenna;
- (b) a duplicate sidewall link S-band receiving antenna; and 15
- (c) a duplicate main link S-band receiving antenna.
8. Apparatus as recited in claim 7 further comprising a third and a fourth antenna port located at substantially right angles to said first and second antenna port. 20
9. A method for determining the relative proportions of two mixed, dielectrically-dissimilar fluids in a container comprising:
- (a) transmitting a low frequency wave substantially in the S-band through said fluids; 25
- (b) measuring a phase shift and attenuation of the wave to obtain the complex dielectric constant of the mixed fluids; and
- (c) calculating the relative proportions of the mixed fluids. 30
10. A method for determining the water content of oil in a flowing pipeline comprising:
- (a) transmitting a low frequency signal substantially in the S-band between a low frequency transmitting antenna and a low frequency receiving antenna, said antennas located within one-half wave length; 35

- (b) transmitting a first high frequency signal substantially in the S-band between a high frequency transmitting antenna and a high frequency receiving antenna, said antennas located within one-half wavelength of each other and in close proximity to said low frequency transmitting and receiving antennas; and
- (c) transmitting a second high frequency signal substantially in the X-band between a second high frequency transmitting antenna and a second high frequency receiving antenna.
11. A method as recited in claim 10 wherein said mixed fluids are water and oil.
12. The method as recited in claim 11 further comprising the steps of:
- measuring a phase shift and attenuation of said low frequency signal;
- measuring a phase shift and attenuation of said first high frequency signal;
- measuring an attenuation of said second high frequency signal;
- calculating a value of an X-band complex dielectric constant of fluid along a wall of the container from said phase shift and attenuation of said low frequency signal;
- calculating a value of an S-band complex dielectric constant of said fluid along said wall from said phase shift and attenuation of said first high frequency signal;
- calculating a volume fraction of water of said fluid along said wall;
- calculating a correction factor to a mixing law;
- calculating a conductivity of said water;
- calculating a value of an S-band complex dielectric constant of fluid within said container; and
- calculating a bulk volume fraction water in said container.
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[54] METHOD AND APPARATUS FOR
INTERFACE LOCATION DETERMINATION

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[21] Appl. No.: 36,837

[22] Filed: Apr. 10, 1987

[51] Int. Cl.⁴ G01V 3/30

[52] U.S. Cl. 324/338; 343/770;
342/175

[58] Field of Search 324/332-344;
342/175; 343/767, 770, 771

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Primary Examiner—Reinhard J. Eisenzopf

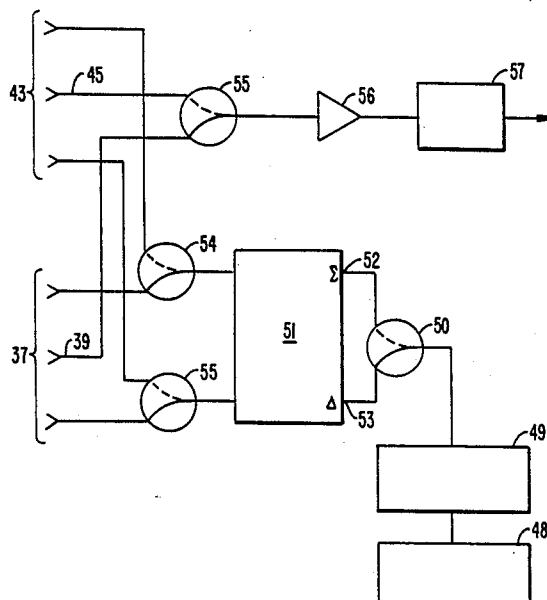
Assistant Examiner—Warren S. Edmonds

Attorney, Agent, or Firm—S. R. La Paglia; E. J. Keeling

[57] ABSTRACT

A method and apparatus for determining the interface between two materials having different dielectric properties, especially in determining the thickness of a hydrocarbon layer on ground water, is disclosed. The apparatus consists of an air-filled, cased surveillance well in which a logging tool is raised and lowered. The logging tool contains an electromagnetic receiving antenna and two transmitting antennas located above and below the receiving antenna. A first wave and a second wave are transmitted from the transmitting antennas. The first and second waves are offset 180° to produce "sum" and "delta" signals using a 180° hybrid. Alternatively, a single wave can be transmitted from a central transmitting antenna to receiving antennas located above and below the transmitting antenna. The received signals are then phase shifted 180° using a 180° hybrid to produce sum and delta signals. As the tool is raised and lowered in the well bore, changes in the sum and delta signals will be observed when an interface is passed. A logging tool for use in petroleum production and exploration wells is also disclosed.

47 Claims, 15 Drawing Sheets



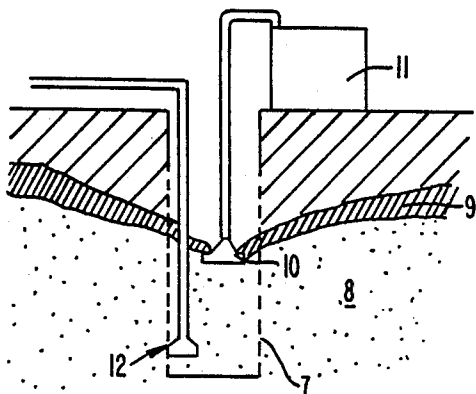


FIG. 1. PRIOR ART

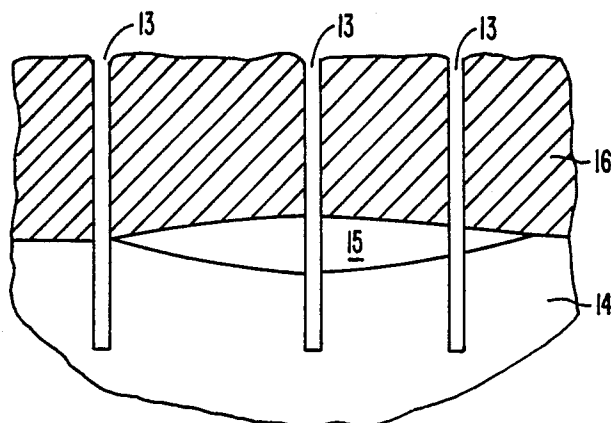


FIG. 2. PRIOR ART

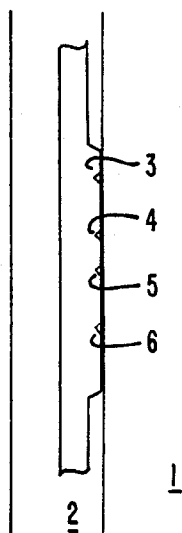


FIG. 3. PRIOR ART

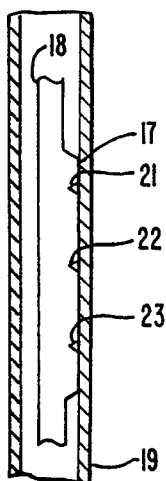


FIG. 4.

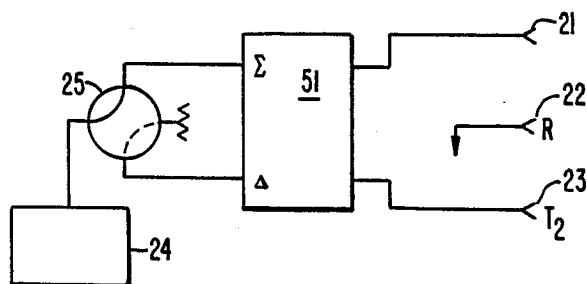


FIG. 5.

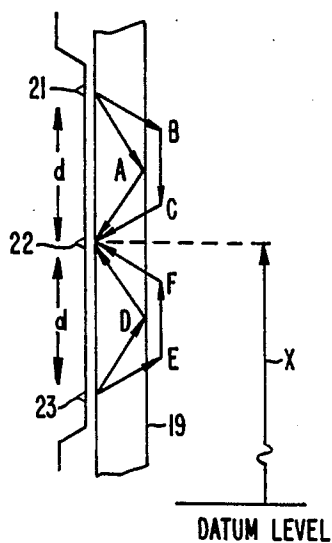


FIG. 6.

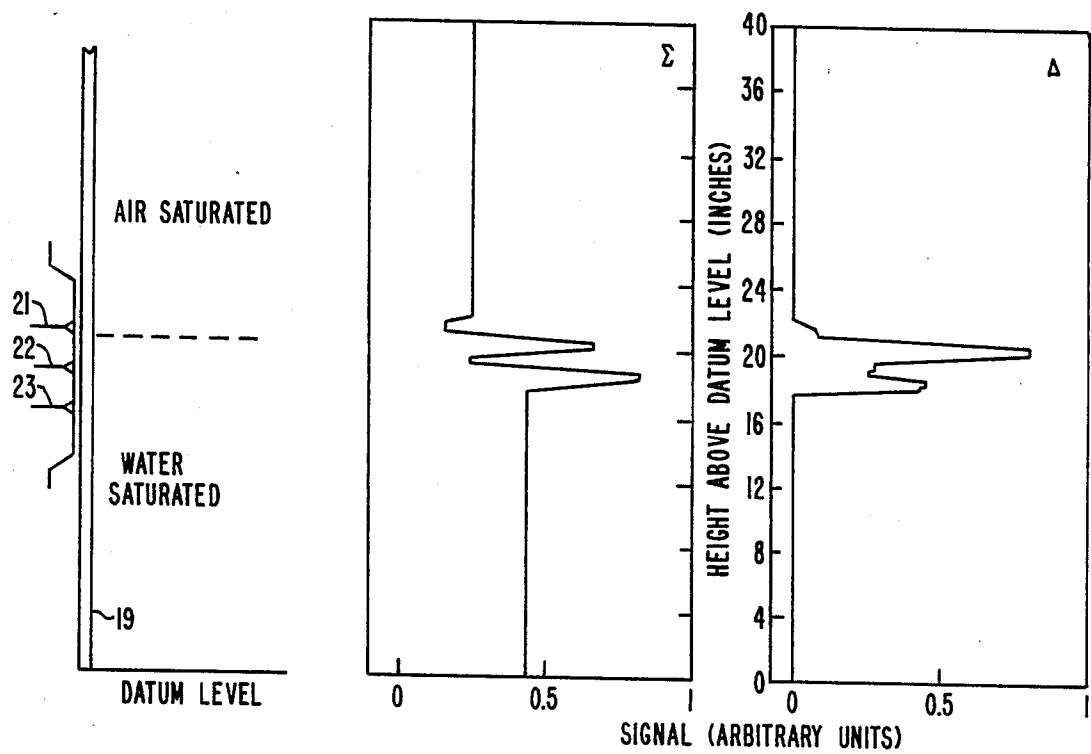


FIG. 7.

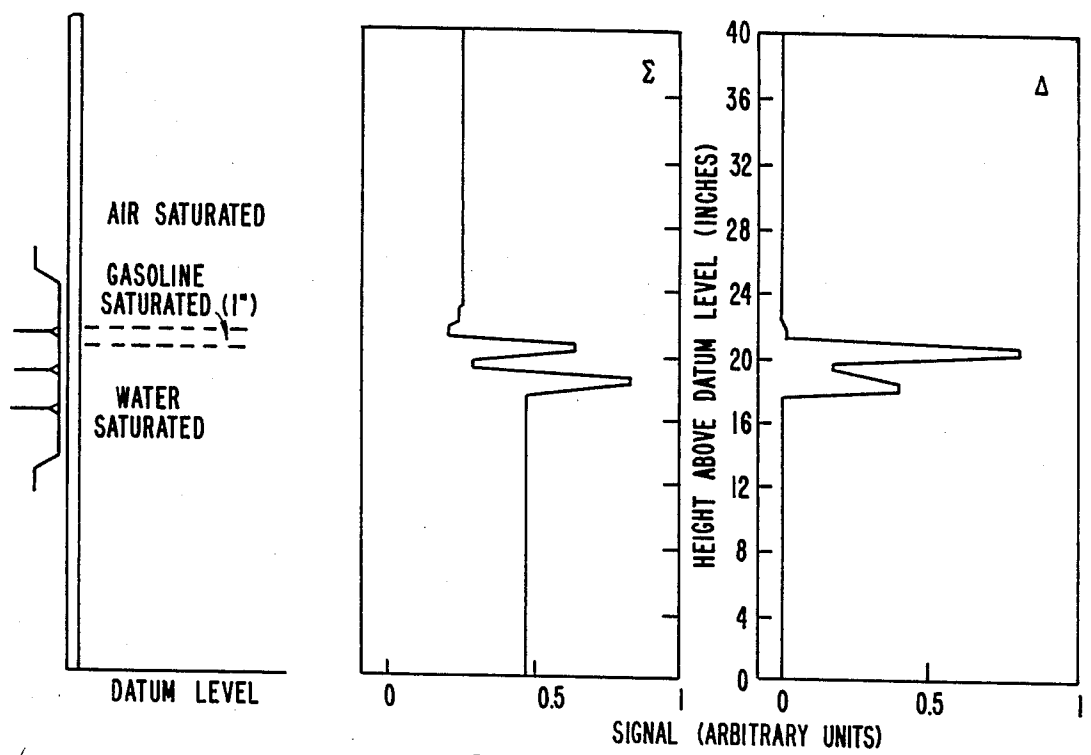


FIG. 8.

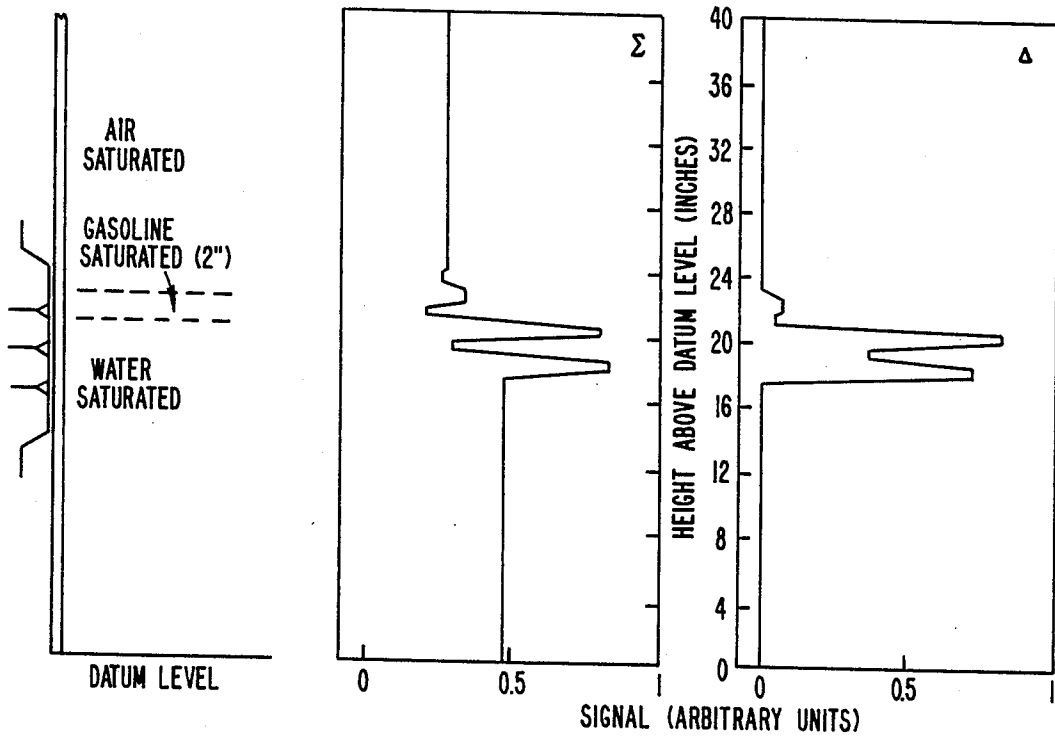


FIG. 9.

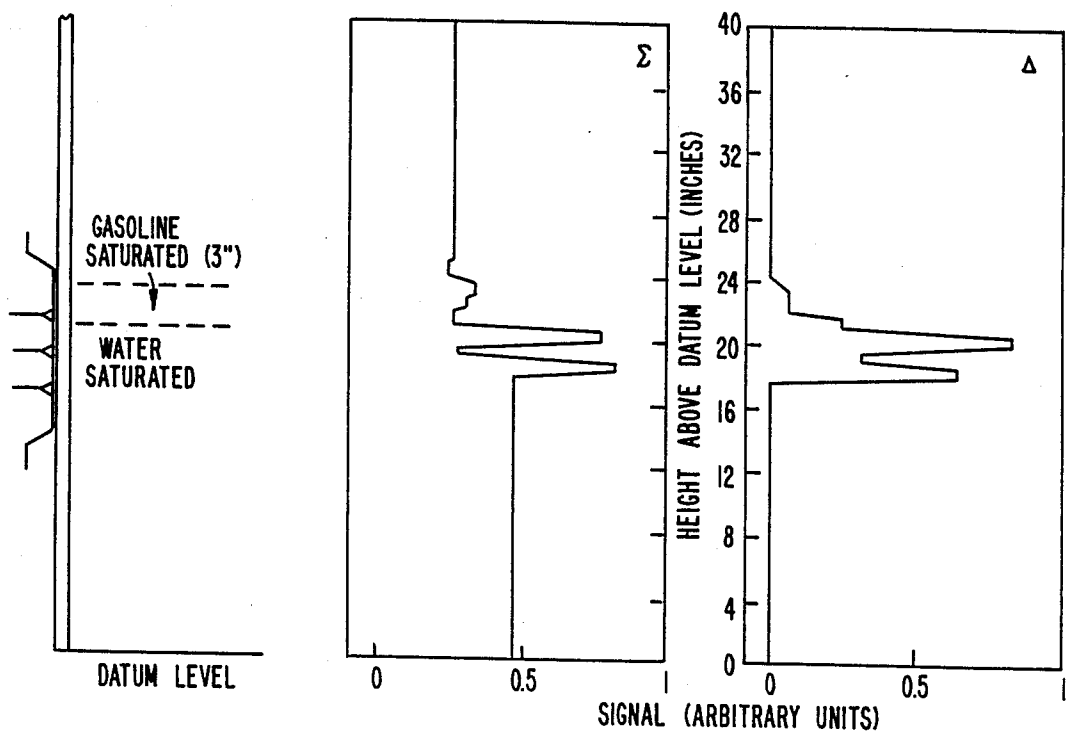


FIG. 10.

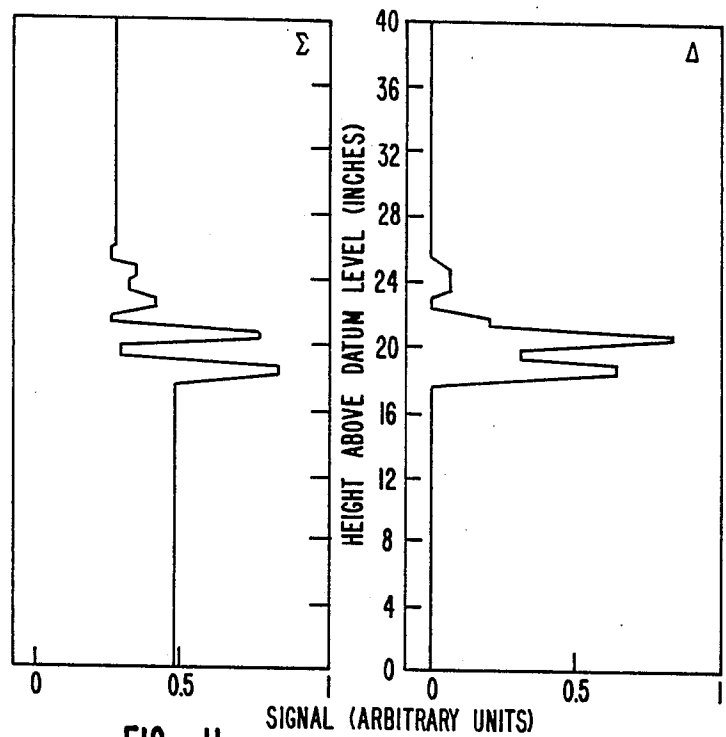
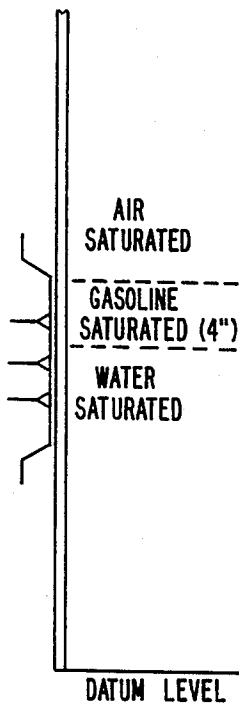


FIG. 11.

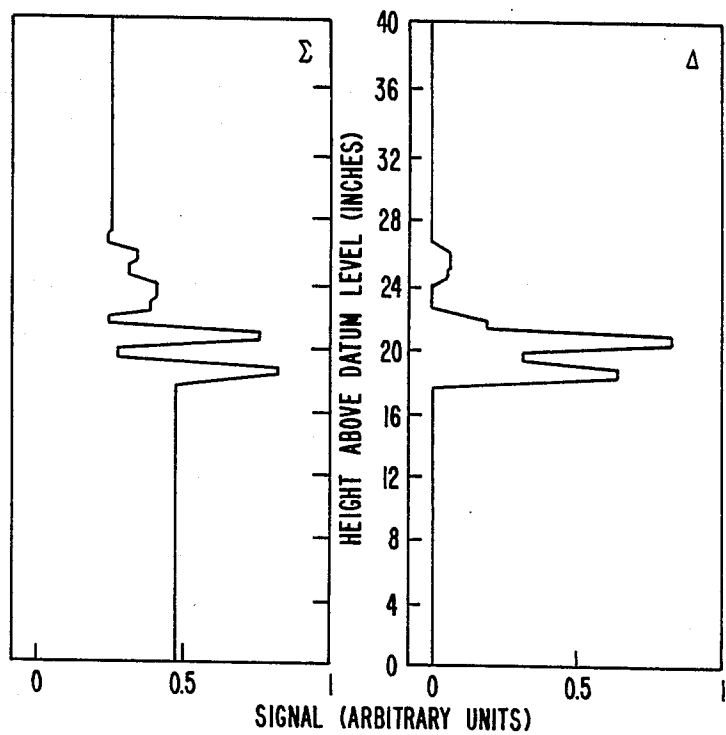
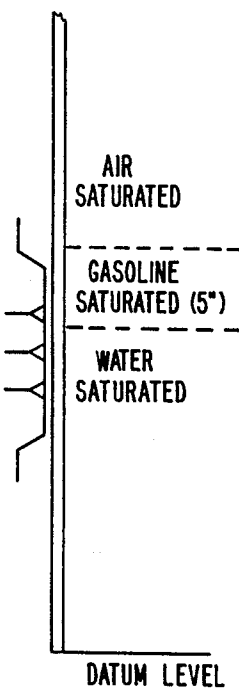


FIG. 12.

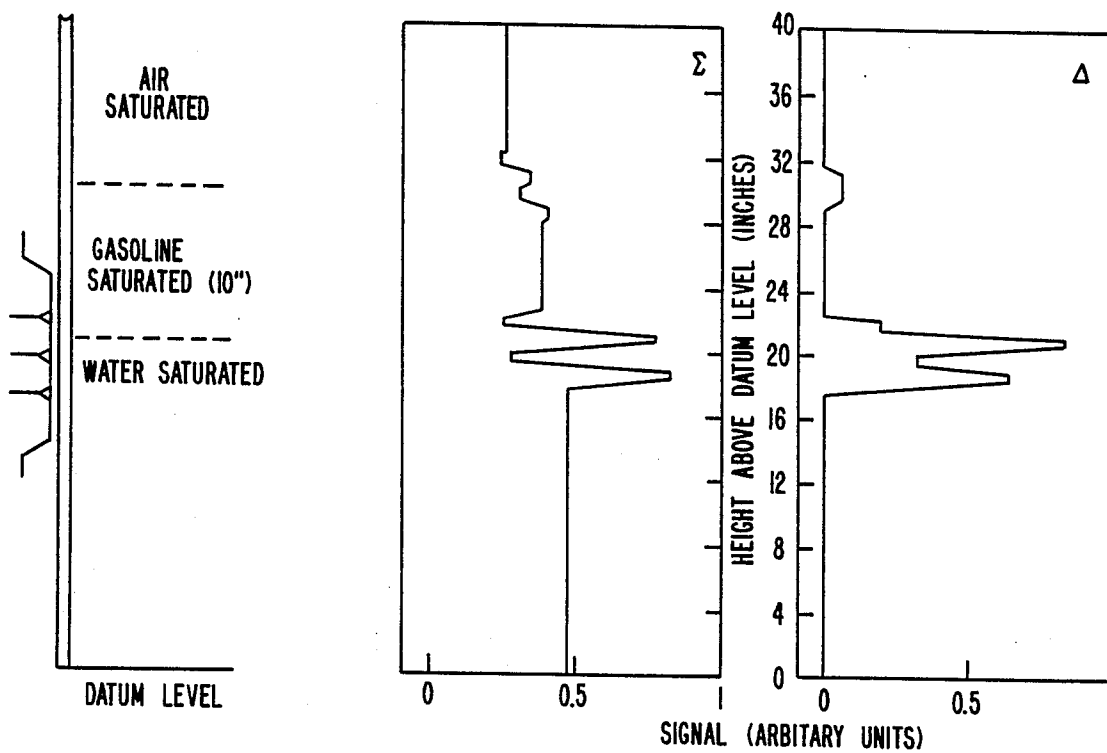


FIG. 13.

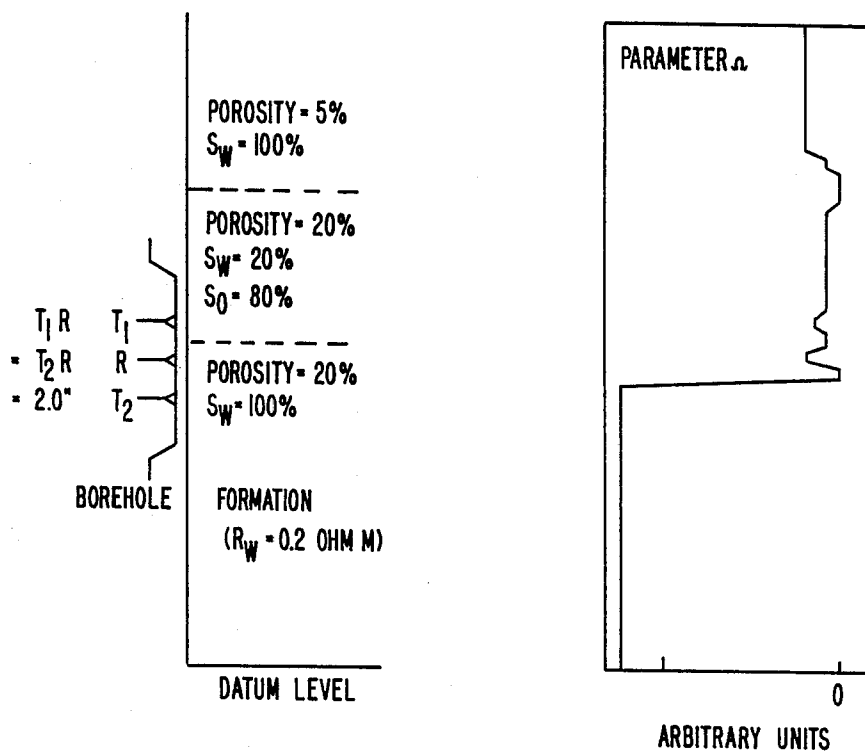


FIG. 25.

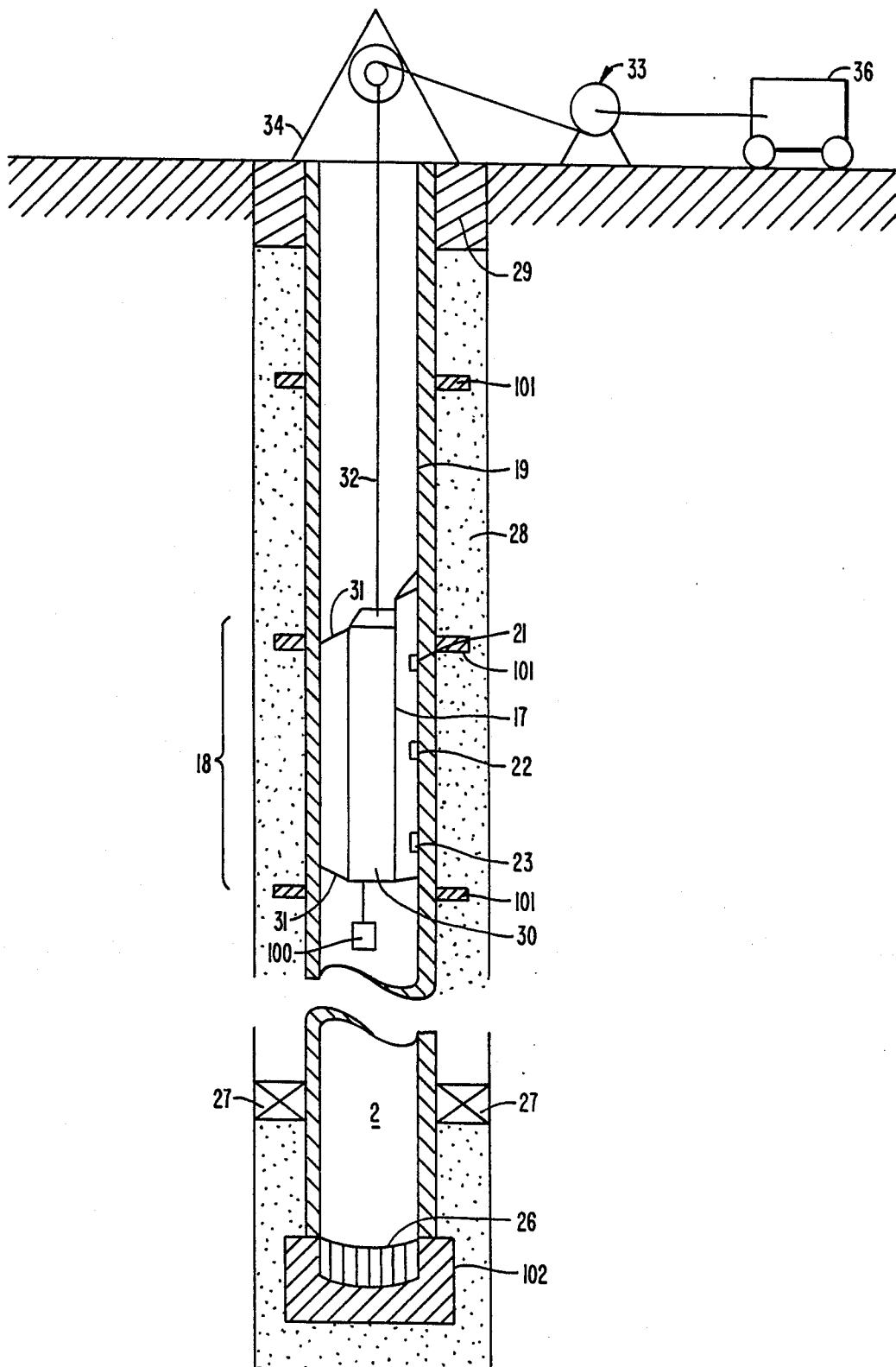


FIG. 14.
TOOL IN THE WELLBORE

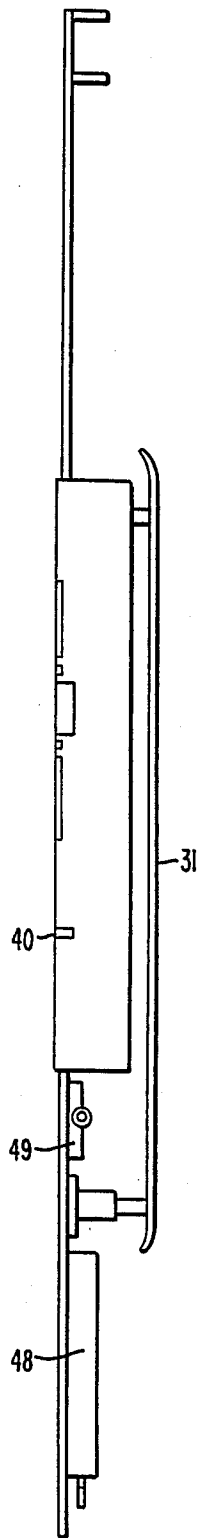


FIG. 15a.

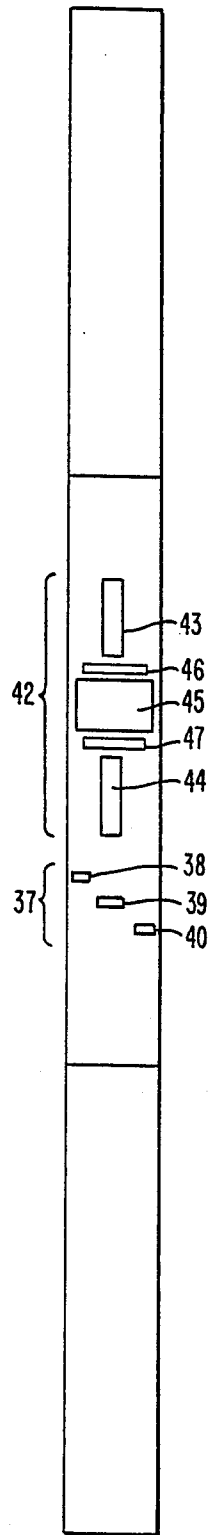


FIG. 15b.

LOGGING TOOL

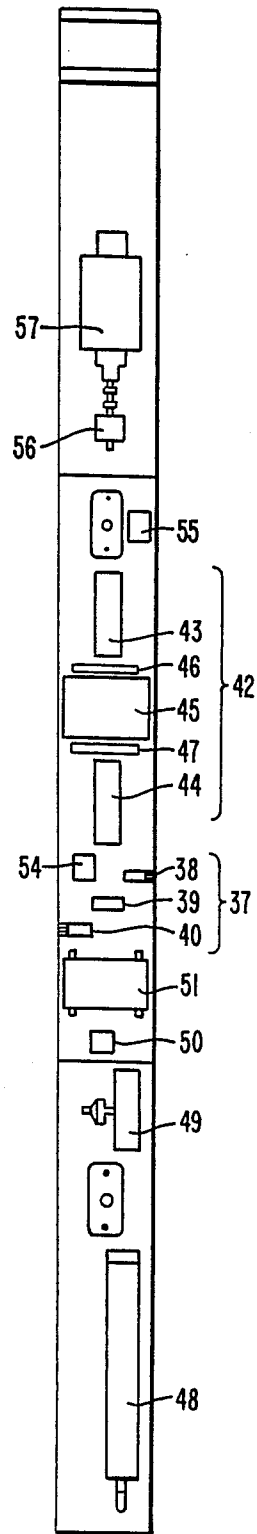


FIG. 15c.

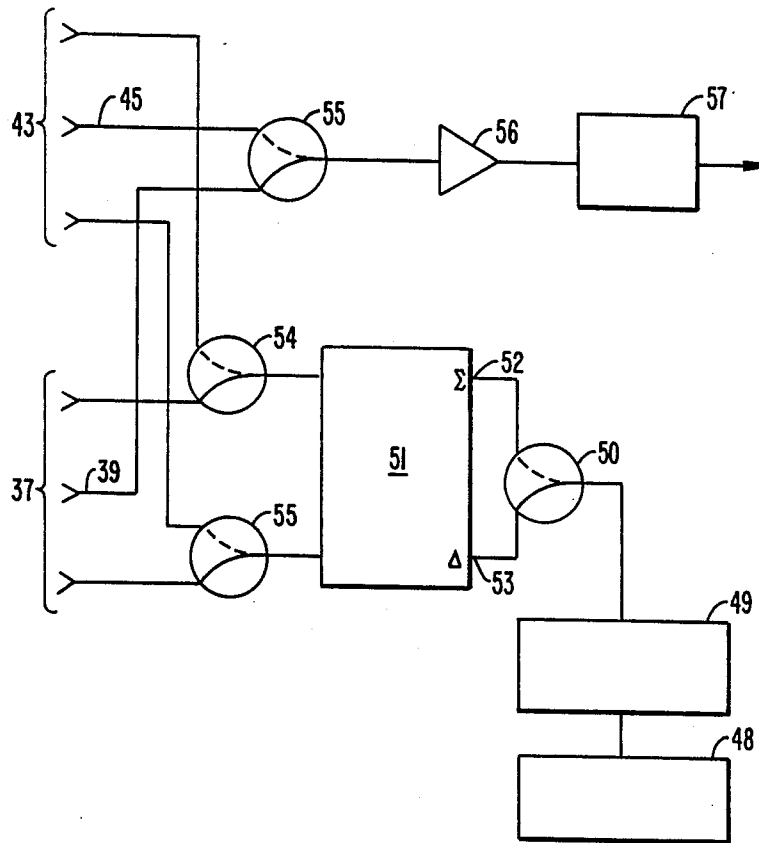


FIG. 16.
RF SYSTEM BLOCK DIAGRAM

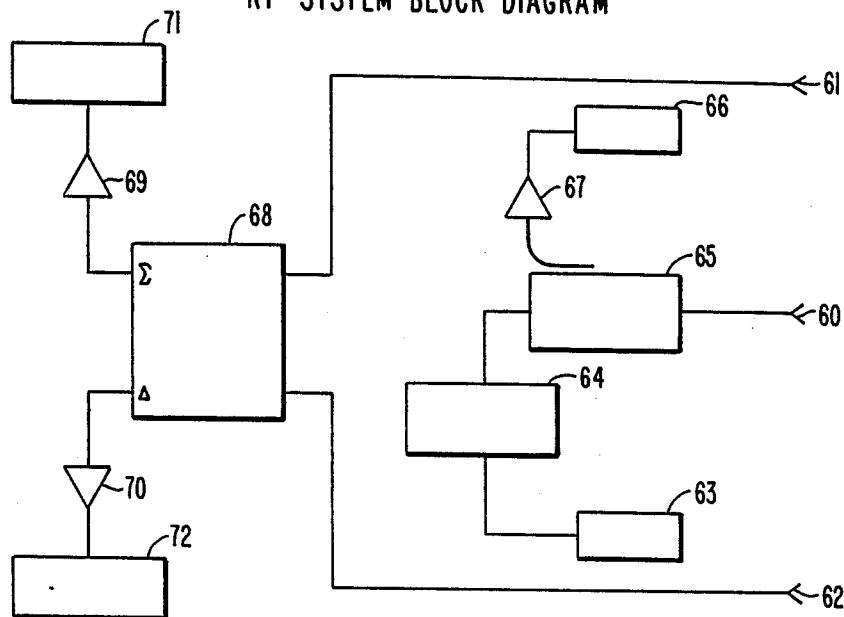
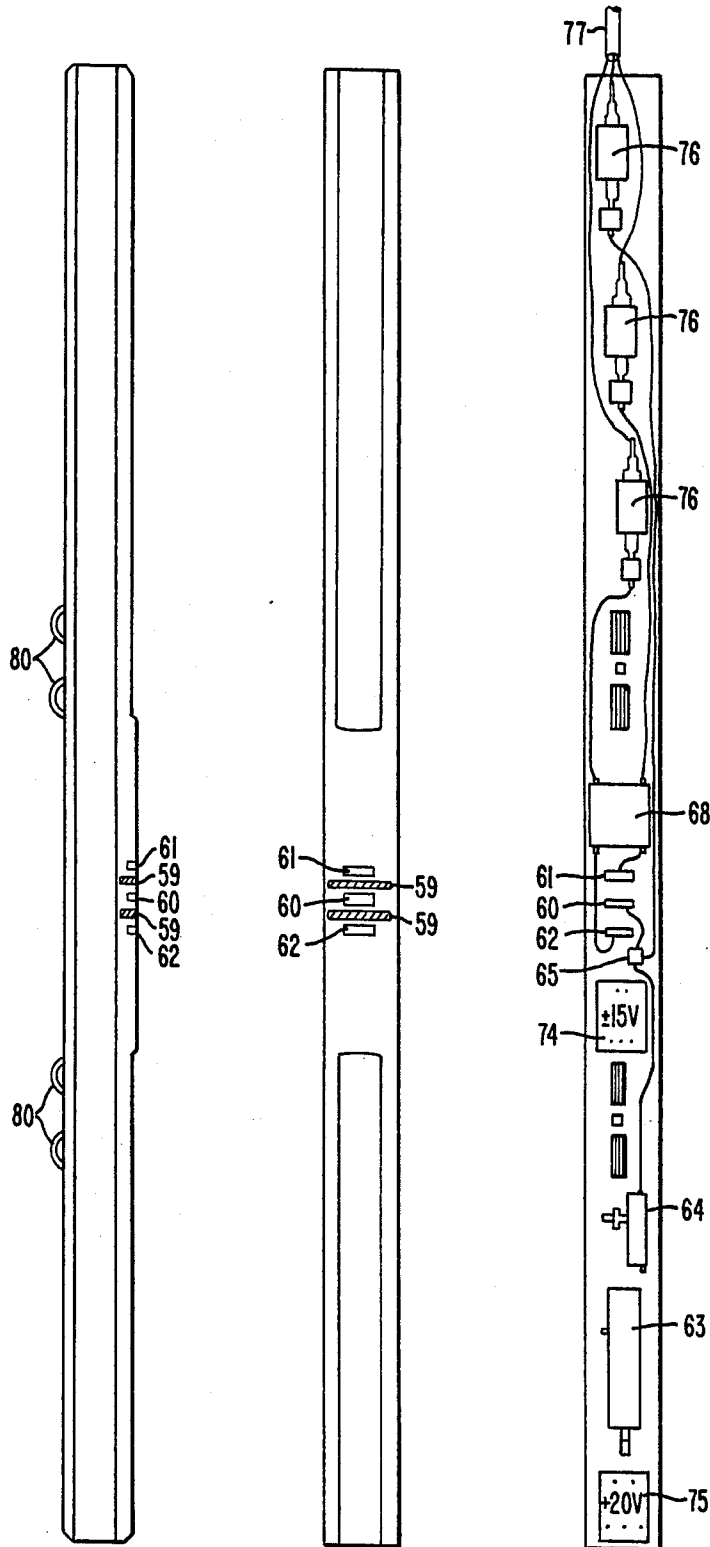


FIG. 18.
RF SYSTEM BLOCK DIAGRAM



LOGGING TOOL

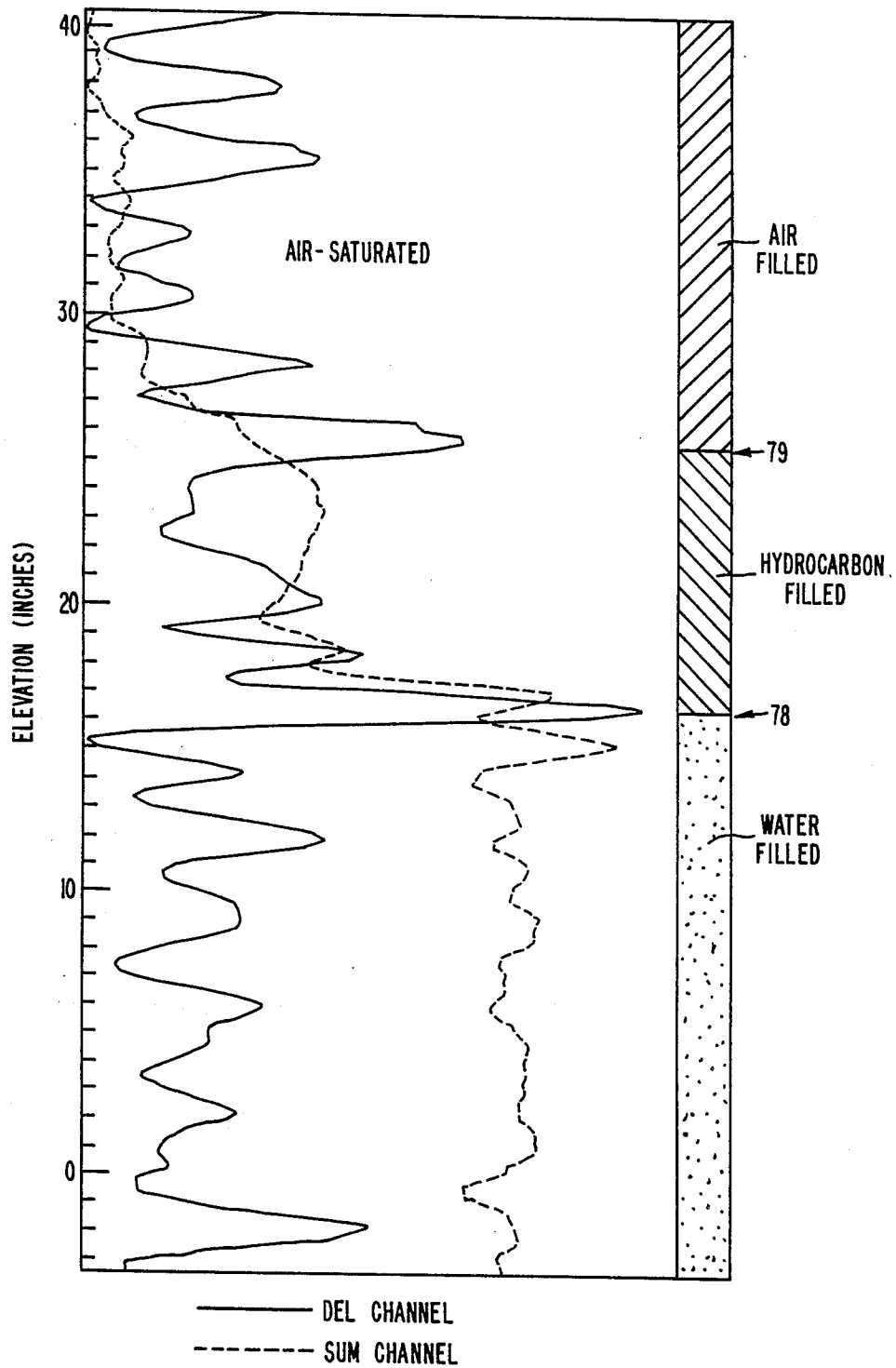


FIG. 19.

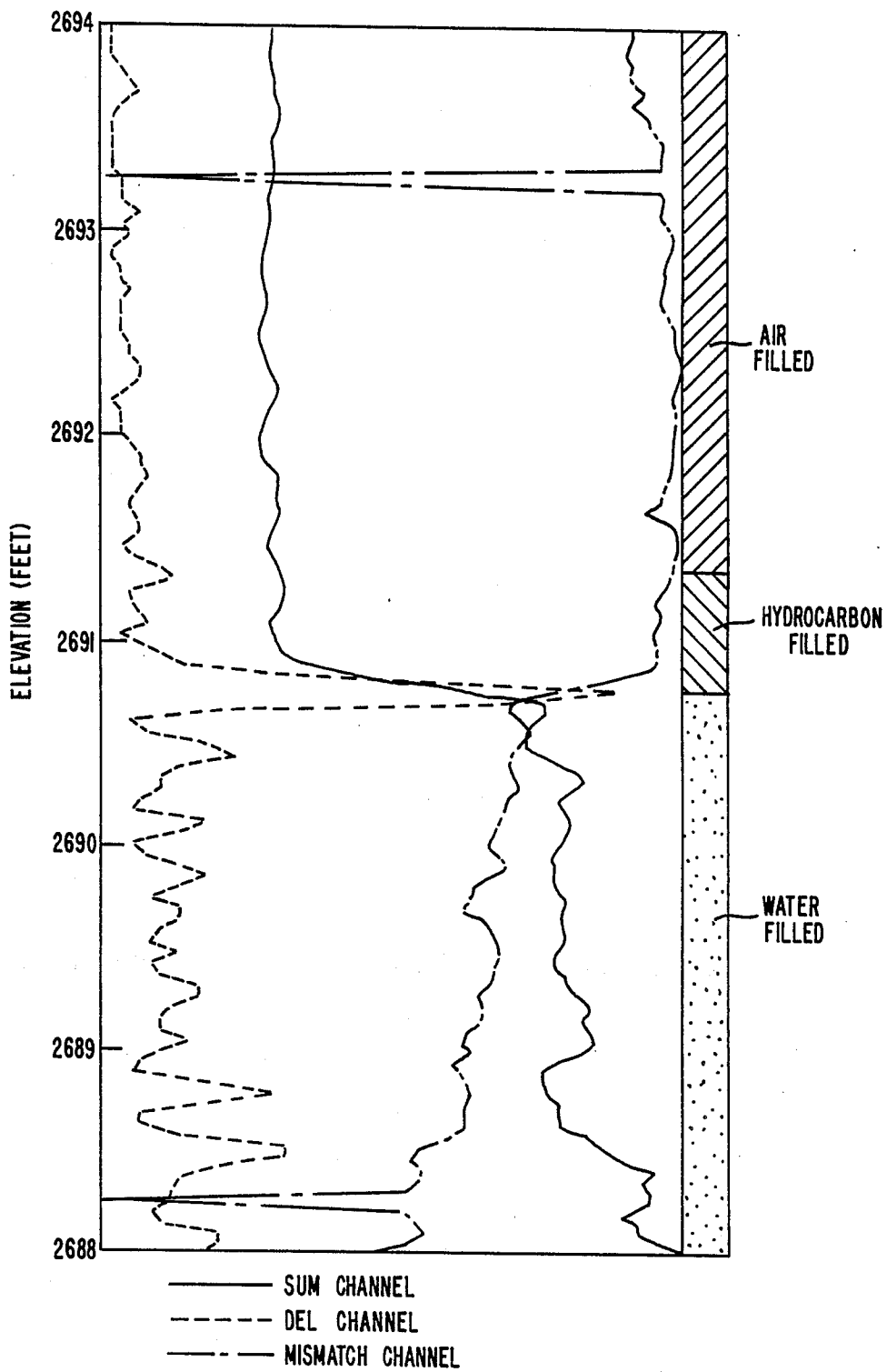


FIG. 20.

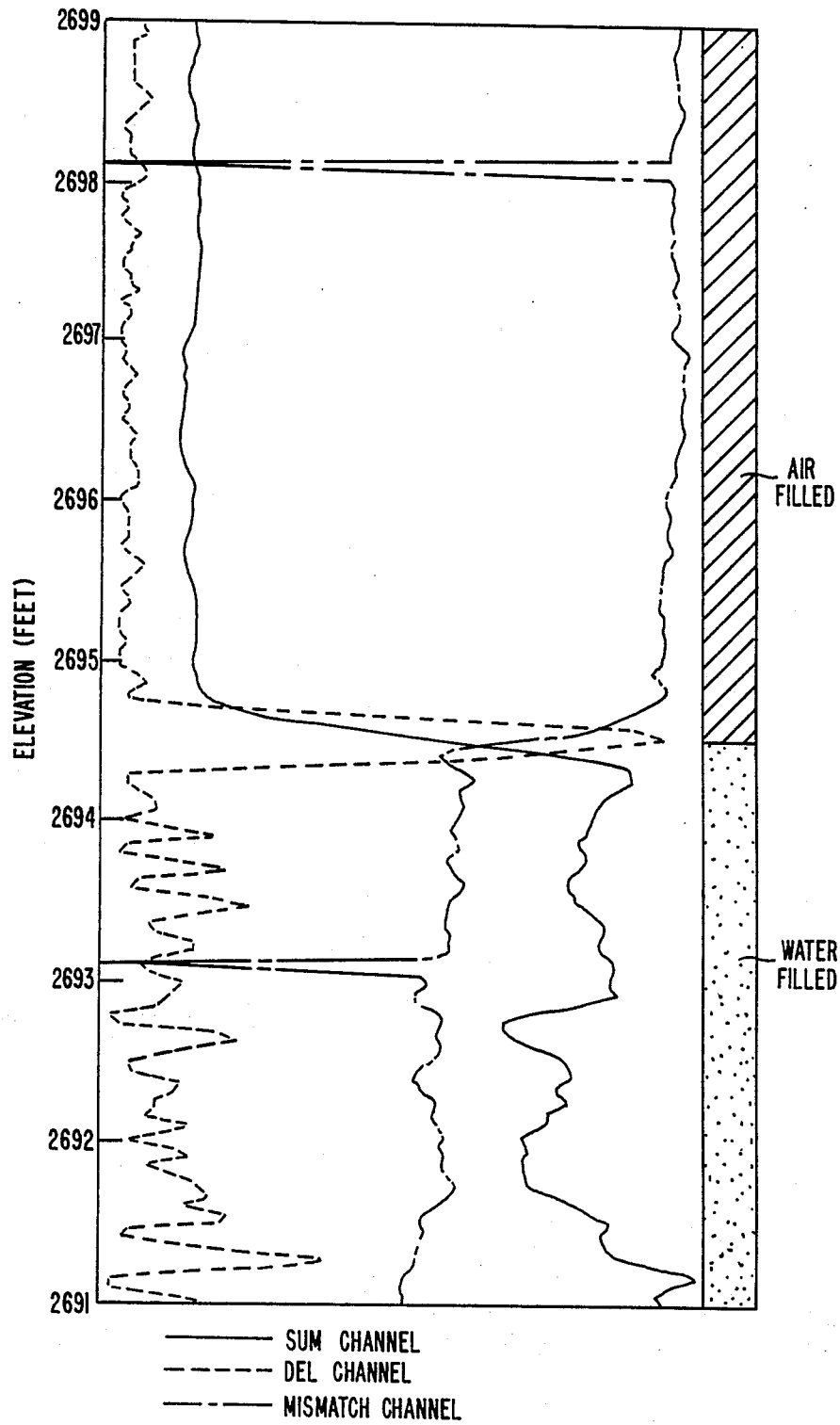


FIG. 21.

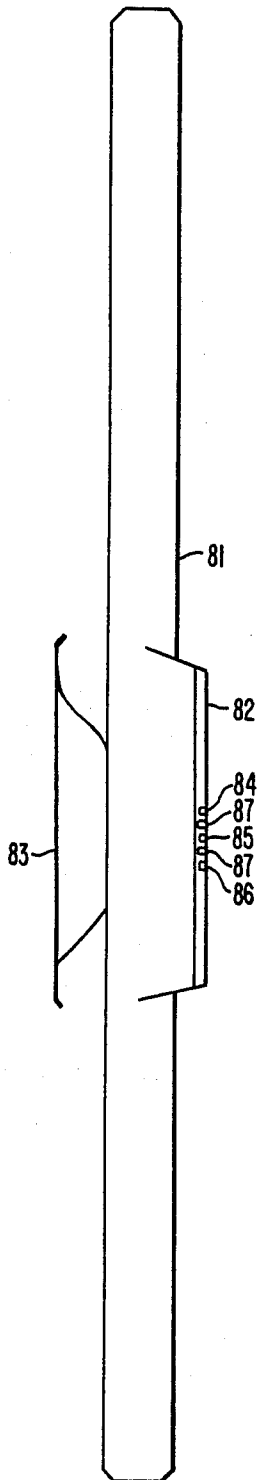


FIG. 22a.

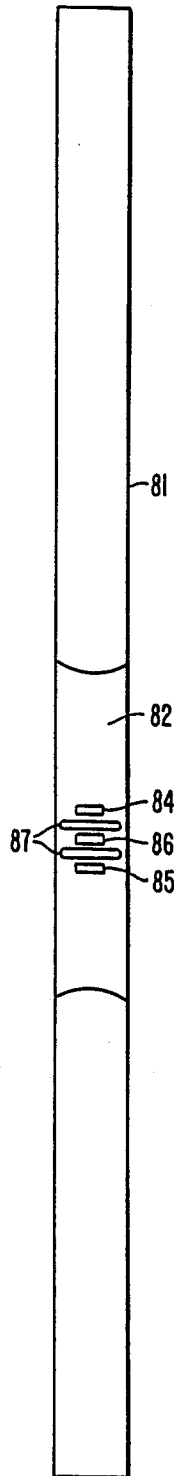


FIG. 22b.

LOGGING TOOL

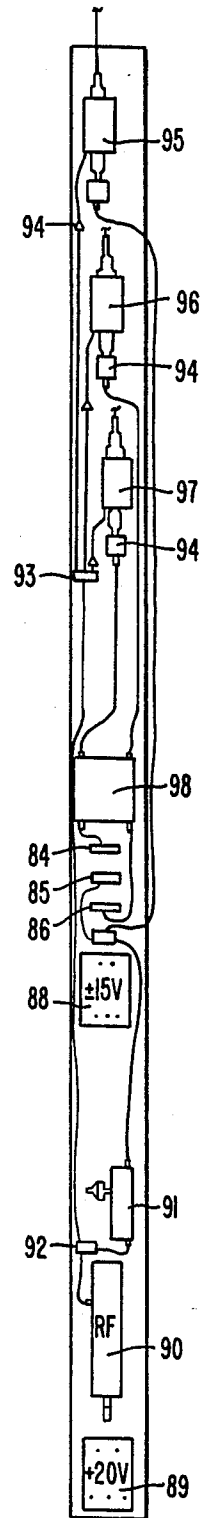
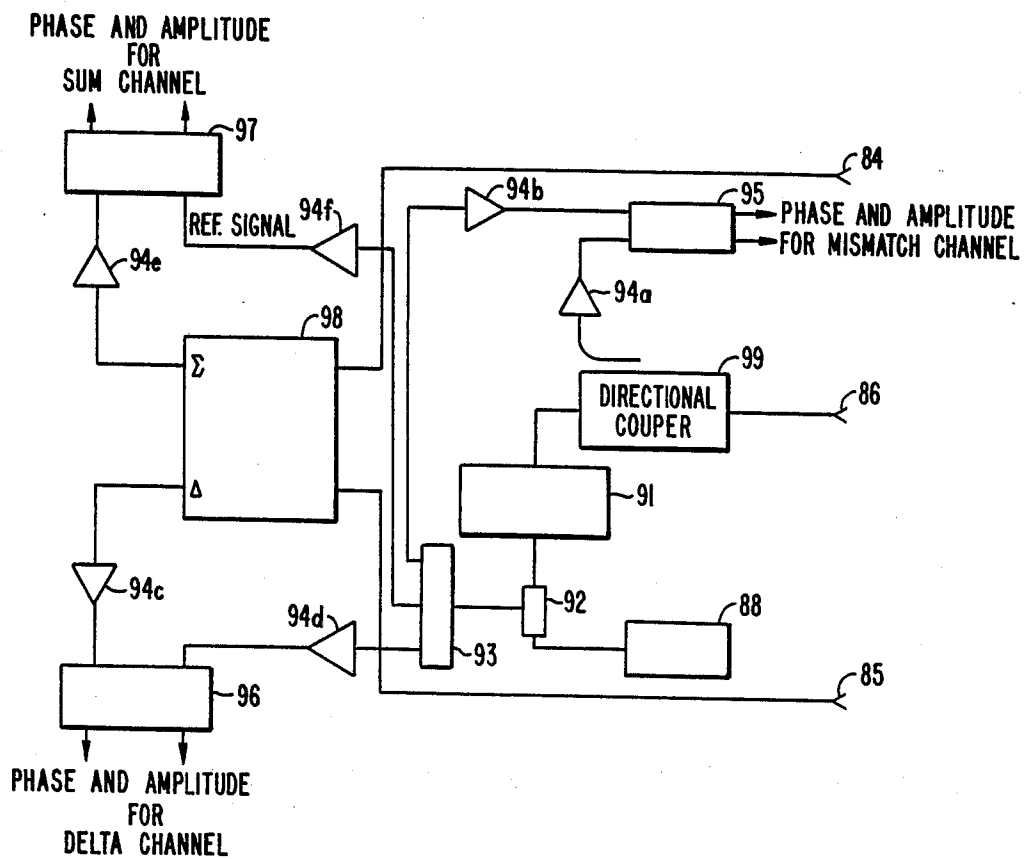


FIG. 22c.

**FIG. 23.**

RF SYSTEM BLOCK DIAGRAM

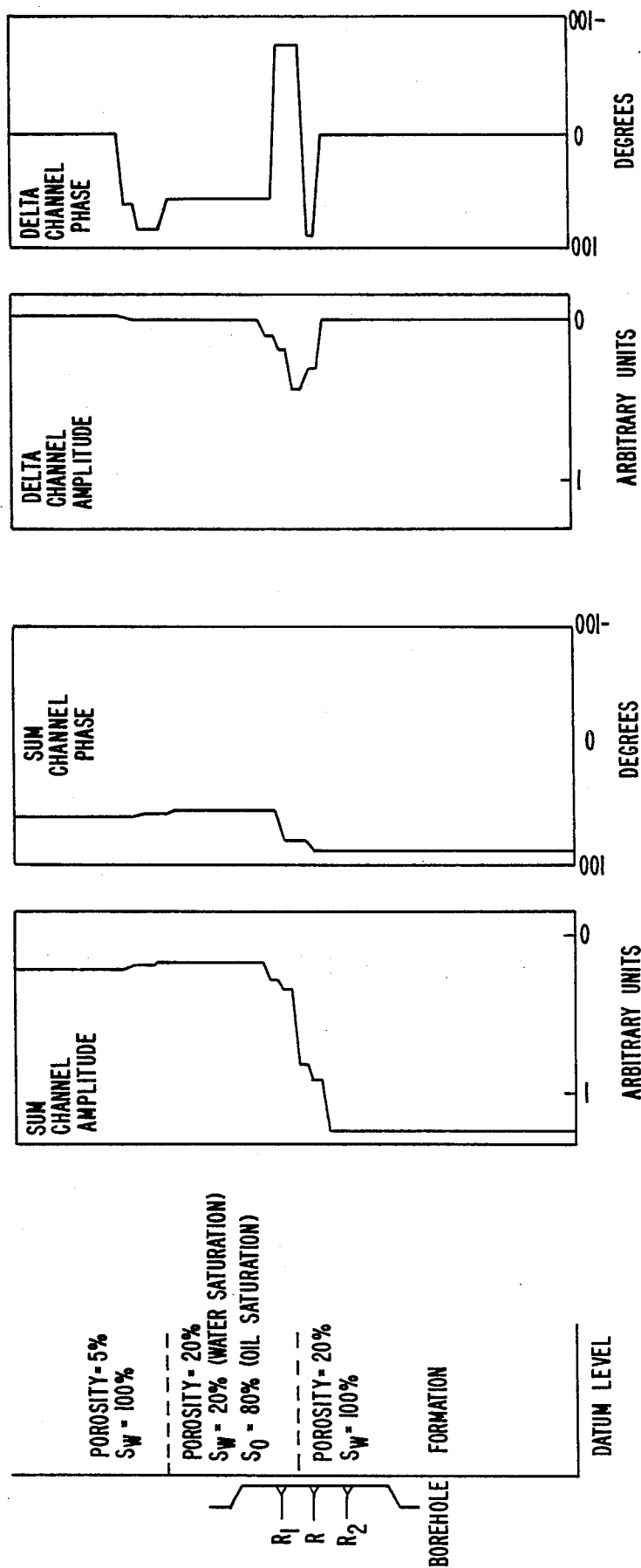


FIG. 24.

METHOD AND APPARATUS FOR INTERFACE LOCATION DETERMINATION

FIELD OF THE INVENTION

This invention is directed generally towards the determination of the location of hydrocarbons in a formation. Specifically, this invention is directed toward the location of fluid interfaces in a hydrocarbon bearing formation.

BACKGROUND OF THE INVENTION

In recent years serious concern for the protection of groundwater from various pollutants has risen. It has been found that contaminants may enter groundwater from various surface locations rendering groundwater unsuitable for drinking or other uses. Among the potential sources of groundwater pollution are leaking underground tanks and, specifically, underground hydrocarbon storage tanks. In many cases, gasoline storage tanks associated with service stations have been found to leak gasoline to the water table.

Light hydrocarbons (e.g., gasoline) lost from refinery tanks, pipelines and service stations gravitates downward to settle on top of the water table in the shape of a plume. In the center of the plume, the hydrocarbon thickness could range up to a couple of feet. Recovery of spilled gasoline is usually effected by pumping the fluid back up to the surface, for example, see U.S. Pat. Nos. 4,630,677; 4,497,370; and 4,273,650.

It is necessary to obtain an estimate of the total quantity of gasoline remaining in the plume at any given time to estimate the volume of hydrocarbon spilled as well as to assess the progress of the cleanup. This can be done by determining the thickness of the plume in several locations over its areal extent. The current technique for doing this is to drill an open well through the plume, and let the water and the gasoline flow into the well and stand to their hydrostatic equilibrium levels. The depths of these fluids and thickness of hydrocarbon in the well can then be measured by simple methods readily known to one skilled in the art (see U.S. Pat. No. 4,213,340).

This wellbore is not representative of the fluid/solid matrix in the formation, however, and the thickness of the free-standing column of gasoline in the open well is generally greater than the actual formation thickness of the spilled fluid [J. Van Dam, "The Migration of Hydrocarbons in a Water-Bearing Stratum", Schwille, F., "Petroleum Contamination of the Subsoil—A Hydrological Problem", both in "The Joint Problems of Oil and Water Industries, Symposium held at Brighton, England (1967), all incorporated by reference herein].

No good means of quantifying this discrepancy exist, but it is believed that the two numbers could differ by a factor of as much as 2 to 4. Using the thickness of the hydrocarbon layer in the wellbore to estimate the amount of hydrocarbon spilled would cause a greatly exaggerated estimate of the amount of gasoline spilled.

It is, therefore, desirable to devise a method and means of accurately determining the actual thickness of hydrocarbon in a subsurface formation.

SUMMARY OF THE INVENTION

We have developed a system to measure the hydrocarbon thickness in the formation itself. The measurement consists of lowering a UHF electromagnetic transmission device down an unperforated air-filled well drilled to the lowest seasonal water table or below. A

non-metallic Well casing of a material such as PVC which allows electromagnetic transmission is used.

The device is raised from the bottom of the well at approximately 10 to 20 feet per minute. Changes in the UHF transmission are recorded as it passes fluid interfaces (e.g., hydrocarbon/water) in the formation. The changes detected are due to the differences in the dielectric properties of the fluid at two locations. The device is based on the "null balance" concept, i.e., as long as the tool is traversing section of the formation of a homogeneous fluid type a "delta" channel signal remains balanced at zero. When the tool traverses a section of the formation where the dielectric characteristics change (i.e., an interface), this balance is perturbed and a finite signal is recorded. A second channel ("sum") indicates the relative magnitude of the dielectric constant of the fluids in the formation.

The first embodiment of the tool is generally cylindrical with the exception of a protruding pad. The curvature of the pad surface matches that of the inside wall of the plastic casing. On the pad are a receiving antenna, and two transmitting antennas located equal distances above and below the receiving antenna. The three antennas are generally identical in all respects, and they are matched to radiate efficiently through the plastic casing.

When the transmitting antennas are energized through a sum port, they transmit radiation having the same amplitude and phase. When energized through a delta port, the amplitudes are again the same, but the phases differ by 180°. Thus, in the sum-mode, the amplitudes of radiation received at the receiving antenna from the two transmitters are added to one another, while in the delta-mode, they are subtracted from one another.

The sensing of the dielectric constant occurs predominantly via the internally reflected paths within the casing wall, which are influenced by the dielectric constant of the formation opposite the antenna. The paths that travel into the formation and then reenter the casing wall make a relatively small contribution.

To operate the device, it is raised and lowered in the wellbore and the elevation of the tool in the wellbore is carefully monitored. The received signal in the sum-mode remains at a constant level until a liquid/liquid or liquid/vapor interface is passed. It shifts to a different magnitude when an interface is crossed corresponding to the change in dielectric constant from one zone to the other. The delta-mode signal remains at zero (i.e., the difference between the transmissions is zero) before passing an interface and becomes finite (i.e., the difference is non-zero) only during the crossing of a interface boundary. The probe thus senses variations in the dielectric constant properties of the formation, rather than its absolute values. With this information it is possible to determine the exact location of liquid/liquid (i.e., water/hydrocarbon) and liquid/vapor (i.e., hydrocarbon/air) interfaces and, therefore, the hydrocarbon layer thickness in the formation.

In a second preferred embodiment, the device is designed to operate on a continuous basis by supplying 2 receiving antennas with a single transmission antenna located between them. Signals are constantly received at the receiving antennas and one of the received signals is phase shifted 180° to create a delta signal.

In summary, a method of determining the location of an interface of materials having differing dielectric

properties is disclosed comprising the steps of transmitting electromagnetic radiation from a first transmitting antenna and a second transmitting antenna in a well-bore, said radiation having a common phase and amplitude, said first transmitting antenna located above said second transmitting antenna; receiving a sum signal at a receiving antenna located between said first transmitting antenna and said second transmitting antenna; transmitting electromagnetic radiation having a common amplitude and phases differing by 180° from said first and said second transmitting antennas; receiving a delta signal at said receiving antenna, and; monitoring said sum and said delta signals.

Alternatively, the method of determining the location of an interface of materials having differing dielectric properties comprises the steps of: transmitting electromagnetic radiation from a transmitting antenna; receiving a first signal at a first receiving antenna located above said transmitting antenna; receiving a second signal at a second receiving antenna located below said receiving antenna; adding said first and said second signals to create a sum signal; phase shifting said first and said second signals a total of 180° to produce phase shifted signals; adding said phase shifted signals to create a delta signal, and; monitoring said sum and said delta signals.

An apparatus for determining the location of an interface of materials having differing dielectric properties is disclosed comprising: a first radiation transmitting means; a second radiation transmitting means, said second radiation transmitting means alternately capable of transmitting radiation of the same phase as said first radiation transmitting means and capable of transmitting radiation 180° out of phase from said first radiation transmitting means; radiation receiving means; and means for monitoring a received signal.

An alternative apparatus for determining the location of an interface of materials having differing dielectric properties is disclosed comprising: a radiation transmitting antenna; a first receiving antenna above said transmitting antenna; a second radiation receiving antenna below said transmitting antenna; means for phase shifting and combining a signal from said first and said second receiving antennas to produce a delta signal; and means for monitoring the delta signal.

The concept of null balanced well logging will also find utility in logging crude oil production or exploration wells. A third embodiment is described that would be utilized in the logging of crude oil and natural gas wells.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross section of a subterranean formation showing the devices used to remove hydrocarbons from groundwater.

FIG. 2 is a cross section of a subterranean formation illustrating the method of determining the volume of hydrocarbons in a subterranean formation.

FIG. 3 illustrates schematically a prior art well logging device used in petroleum production wells.

FIG. 4 is a schematic diagram generally illustrating the layout of the present well logging tool.

FIG. 5 is a generalized RF diagram for the present invention.

FIG. 6 schematically illustrates the method of operation of the present invention.

FIGS. 7 to 13 are idealized (i.e., numerical simulations) well logs using the present invention for hydro-

carbon layer thickness of 0", 1", 2", 3", 4", 5", and 10", respectively. The formation conditions for the corresponding depths are shown in each Figure on the left side of the FIGURE.

FIG. 14 shows a schematic of the present invention in a subsurface formation.

FIGS. 15a-c are a detailed drawing of the first preferred embodiment in side view (FIG. 15a), front view (FIG. 15b) and cutaway rear view (FIG. 15c).

FIG. 16 is a detailed RF diagram of the first preferred embodiment.

FIGS. 17a-c are detailed drawing of the second preferred embodiment in side view (FIG. 17a), front view (FIG. 17b) and cutaway rear view (FIG. 17c).

FIG. 18 is a detailed RF diagram of the second preferred embodiment.

FIG. 19 is a well log obtained with the second preferred embodiment in a laboratory logging well in a model formation with a sand matrix.

FIG. 20 is a well log obtained with the second preferred embodiment in a subsurface well in Boise, Id.

FIG. 21 is a well log obtained with the second preferred embodiment in a well in Boise, Idaho with no hydrocarbon layer.

FIGS. 22a-c are detailed drawing of the third preferred embodiment inside view (FIG. 22a), front view (FIG. 22b), and cutaway rear view (FIG. 22c).

FIG. 23 is an RF diagram for the third preferred embodiment.

FIG. 24 is an idealized (i.e., numerical simulation) well log for the third preferred embodiment.

FIG. 25 is a simulated well log illustrating the use of an "omega" channel.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Recovery of spilled hydrocarbons is usually effected by pumping the fluid back up to the surface, as shown in FIG. 1. A slotted well liner 7 is inserted into a subterranean formation. The formation contains a water saturated region 8, and a hydrocarbon saturated region 9. A recovery pump 10 pumps the hydrocarbon 9 to a surface storage facility 11. A water table depression pump 12 is also used in most applications. The water table depression pump serves to draw down the water table below its natural level. This creates a "sink" in which hydrocarbon will tend to accumulate.

In order to determine the effectiveness of this recovery procedure, it is necessary to obtain an estimate of the total quantity of gasoline remaining in the plume at any given time. This can be done as shown in FIG. 2 by determining the thickness of the plume in several locations at a number of surveillance wells 13. The current technique for determining the thickness of a hydrocarbon layer in a surveillance well is to allow the water and the gasoline flow into the surveillance well and stand at their hydrostatic equilibrium levels. The thickness of these fluid layers in the well can then be measured by simple methods. However, the thickness of a free-standing column of gasoline is known to be substantially greater than the actual formation thickness of the spilled fluid, causing a greatly exaggerated estimate of the amount of hydrocarbon spilled.

Some conventional logging tools employing electromagnetic or acoustic waves to probe a petroleum production formation are shown in FIG. 3. The wave is transmitted into the formation 1 from the borehole 2 from an antenna 3, and is received at another point 4

above or below the transmitter after the wave has traversed some distance in the formation. The amplitude and the phase of the received signal contain information (dielectric constant and conductivity in case of electromagnetic waves, velocity and attenuation in case of acoustic waves) about the formation. A duplicate receiving location 5 is usually employed, thereby obtaining measurements that eliminate certain unknown factors. Additionally by employing a duplicate transmitting location 6 (above or below the receiver pair), the effects of alternate upward and downward transmissions are averaged to achieve "borehole compensation". Examples of such tools are the Schlumberger TM Borehole-compensated BBHC) Sonic Tool, the Electromagnetic Propagation Tool (EPT), and the electromagnetic tool called the Deep Propagation Tool (DPT).

The EPT or DPT device is especially useful in locating an interface between materials with radically different dielectric properties (e.g., water and gasoline). However, the above-described devices have not been utilized in locating materials in groundwater and, more importantly, for reasons which are illustrated below, this type of tool is not useful in locating the interface between materials having similar dielectric properties (e.g., air and gasoline). Therefore, the prior art devices would not be useful in determining the thickness of a hydrocarbon layer in groundwater because they measure absolute properties of the formation and it would not be possible to locate the air/hydrocarbon interface as a result of the tools' insensitivity to small changes in dielectric properties.

In a groundwater formation, assuming that the formation is lossless, the sand matrix, the water, and the gasoline can be represented by real dielectric constants ϵ_m , ϵ_w and ϵ_g , respectively. The following simple mixing laws can then be employed:

(1) For the water zone ("Zone I") it is assumed that the sand matrix is fully saturated with water, so that the dielectric constant for this zone (ϵ_I) is

$$\epsilon_I = [(1 - \phi)\epsilon_m^{\frac{1}{2}} + \phi\epsilon_w^{\frac{1}{2}}]^2 \quad (1)$$

where ϕ is porosity (i.e., the void volume fraction of the matrix).

(2) For the contaminant zone ("Zone II") it is assumed that the sand matrix is fully saturated with gasoline, so that the dielectric constant for this zone (ϵ_{II}) is

$$\epsilon_{II} = [(1 - \phi)\epsilon_m^{\frac{1}{2}} + \phi\epsilon_g^{\frac{1}{2}}]^2 \quad (2)$$

(3) For the air zone ("Zone III") it is assumed that the sand matrix is completely dry (air-filled), so the dielectric constant for this zone (ϵ_{III}) is

$$\epsilon_{III} = [(1 - \phi)\epsilon_m^{\frac{1}{2}} + \phi]^2 \quad (3)$$

Typical values of ϵ_m , ϵ_w , and ϵ_g are $\epsilon_m = 4.6$, $\epsilon_w = 78$, $\epsilon_g = 2.4$. For $\phi = 30\%$, we find: $\epsilon_I = 17.2$, $\epsilon_{II} = 3.9$, $\epsilon_{III} = 3.2$.

The problem with prior art logging tools becomes immediately obvious from the above. While the contrast between Zones I and II is great, the contrast between Zones II and III is marginal. Such a contrast would not be noticeable by the conventional electromagnetic (dielectric) logging tools, even if such tools were capable of logging through a plastic casing. The Schlumberger Electromagnetic Propagation Tool, for example, is a padtype tool and is designed to operate

when in direct contact with the formation. The antennas used herein are matched to look through a plastic casing into a formation, while EPT antennas are matched to look directly into the formation (with the size of the slot, the size of the cavity, and the type of filling). Without the ability to discriminate between Zones II and III (the air and gasoline zone), it would be impossible to quantify the thickness of the plume. The Schlumberger DPT tool is a centralized tool and uses a relatively low frequency transmission device for the purpose of deep penetration, but results in poor spatial resolution. It is, therefore, not useful for the present purpose where vertical resolution to a few inches is required.

FIG. 4 schematically illustrates the well logging tool described herein. The probe is a pad 17 on the logging tool 18 that is inserted in plastic well casing 19. The curvature of the pad surface matches that of the inside wall of the plastic casing. On the pad are a receiving antenna 22 and two transmitting antennas 21 and 23 which are located equal distances above and below the receiving antenna.

FIG. 5 is a simplified RF (radio frequency) block diagram for the device. A signal from source 24 and transfer switch 25 is transmitted to either the sum (Σ) or the difference (Δ) channel of 180° hybrid 51. The hybrid is a passive four-port device which, if fed through the Σ port, divides the power into two equal portions whose amplitudes are in phase; if fed through the Δ port, these amplitudes are 180° out of phase. Receiving antenna 22 monitors the transmitted signals.

Referring now to FIG. 6, it can be assumed that the three antennas are identical in all respects, and that they are matched to radiate efficiently into the plastic material (having a dielectric constant ϵ_p). It can be further assumed that the antennas can be treated as point sources, and that the propagation of radiation can be treated in terms of ray optics. FIG. 6 shows the signal paths from antenna 21 to 22, and from antenna 23 to 22 into and through the casing well 19. The paths through the formation (21, B, C, 22 and 23, E, F, 22) suffer larger geometric spread and one additional reflection (at the plastic/formation interface) as compared to the paths in the plastic material (21, A, 22 and 23, D, 22). Therefore, the contribution of the former paths can be neglected.

If x is the coordinate of the receiving antenna measured from some reference depth in the well bore (as shown in FIG. 6), let $\epsilon(x)$ be the dielectric constant of the formation at location x and let d be the distance between the receiving and transmitting antennas (as shown in FIG. 6). When the wall of the casing 19 is thin, the formation is in the near field of the antennas, and influences their radiation efficiency. This efficiency is difficult to quantify. However, we can obtain an ad hoc estimate for this efficiency by assuming that the impedance contrast between the plastic and the formation in the near field of the radiating antenna causes the reflected radiation to go back into the antennas and onto the source. This efficiency is thus equal to the ratio of the amplitude transmitted into the formation to that of the amplitude of the forward-traveling wave at the antenna aperture, which is assumed to be unity. Thus, the efficiency [$\eta(x)$] is:

$$\eta(x) = 1 - \frac{\sqrt{\epsilon(x)} - \sqrt{\epsilon_p}}{\sqrt{\epsilon(x)} + \sqrt{\epsilon_p}} \quad (4)$$

$$= \frac{2\sqrt{\epsilon_p}}{\sqrt{\epsilon(x)} + \sqrt{\epsilon_p}}$$

This expression assumes that $\epsilon(x)$ is always greater than ϵ_p which will always be true for a plastic cased well. This efficiency also applies to the receiving antenna.

The power received at the receiving antenna for the sum and the delta modes respectively can now be written as

$$\Sigma(x) = C \left[\eta(x)\eta(x+d) \frac{\sqrt{\epsilon(x+d/2)} - \sqrt{\epsilon_p}}{\sqrt{\epsilon(x+d/2)} + \sqrt{\epsilon_p}} + \eta(x)\eta(x-d) \frac{\sqrt{\epsilon(x-d/2)} - \sqrt{\epsilon_p}}{\sqrt{\epsilon(x-d/2)} + \sqrt{\epsilon_p}} \right]^2 \quad (5)$$

$$\Delta(x) = C \left[\eta(x)\eta(x+d) \frac{\sqrt{\epsilon(x+d/2)} - \sqrt{\epsilon_p}}{\sqrt{\epsilon(x+d/2)} + \sqrt{\epsilon_p}} - \eta(x)\eta(x-d) \frac{\sqrt{\epsilon(x-d/2)} - \sqrt{\epsilon_p}}{\sqrt{\epsilon(x-d/2)} + \sqrt{\epsilon_p}} \right]^2 \quad (6)$$

where C is a geometric constant which need not be determined since the absolute value of Σ and Δ will not be important (i.e., only changes in these values will be important).

Equations (5) and (6) can now be used to generate the series of idealized logs discussed below. The logs below assume $\epsilon_I=17.2$, $\epsilon_{II}=3.9$, $\epsilon_{III}=3.2$ and $\epsilon_p=2.0$, $d=2''$, the thickness of the plastic $=\frac{1}{4}''$, and the dry sand porosity is 30%. The probe response was calculated at every 0.1 inch interval, and then a fivepoint averaging was applied to the calculated data in order to partially simulate the effect of a finite antenna aperture.

In FIG. 7 there is no spilled hydrocarbon layer, i.e., this is the case of a "clean" water table. As the tool is moved upward through a clean water table and into the air-saturated portion, the sum signal goes through a twin peak, and then shifts to a constant lower level. The delta signal also goes through a twin peak, and then drops back to zero.

The separation distance between antennas is the principal parameter defining the spatial resolution of the probe. In these idealized well logs, this distance is 4 inches. FIGS. 7 to 13 show the evolving features of the logs as the thickness of the spilled layer gradually increases and exceeds the distance between the transmitting antennas.

In the sum channel, we see the gradual emergence of two twin-peaks, corresponding to the two formation zones of fluids with different dielectric properties. These two twin-peaks are clearly discernible starting in FIG. 11, where the thickness of the spilled layer equals 2 times. In FIG. 13, we observe three fully developed segments of constant signal levels, corresponding to the water, the hydrocarbon, and the dry zones.

For the delta channel we observe, again beginning in FIG. 11, the emergence of a distinct peak feature for the hydrocarbon layer/dry sand interface. By FIG. 13, the three formation zones have been well demarcated.

Lastly, we note that the probe response is a convolution of the array pattern of the antenna arrays 21, 22, and 23 with the dielectric profile $\Sigma(x)$. Thus, it may be possible to employ a deconvolution procedure to recover this profile even when the spilled layer thickness

is somewhat smaller than the distance between the transmitting antennas.

While the above discussion reeters to the logging tool in general terms, prototype tools have been constructed in order to refine the design of the logging tool and its related equipment. FIG. 14 illustrates the logging tool as it is being raised and lowered (preferably raised to prevent hang-up) in the well. Wellbore 2 is completed with a non-perforated casing 19 which is Schedule 40 PVC. The bottom of the casing is isolated with cap 26 (PVC) and the casing is held centrally within the wellbore with non-metallic centralizers 27. A cement plug 102 is preformed around the casing to weight it below the water table. In the preferred embodiment the wellbore is 12" in diameter and there is a 3.75" annulus between the casing and the wellbore.

It is important to evenly sand/gravel pack the annulus of the well in order to achieve good results with the invention. The grain size of the gravel (or sand) 28 is chosen to match as closely as possible that of the surrounding formation. In the preferred embodiment for a formation in Boise, Id., this is chosen to be between 20 to 60 mesh. Cement grout seal 29 is installed above the sandpack for the purpose of preventing the intrusion of surface waters into the gravel pack.

The logging tool 18 consists of antenna pad 17 mounted on body 30. Antenna 21, 22 and 23 are contained within the antenna pad. Pressure arms 31 are provided in order to keep the tool stable and pressed against the casing in the well. The tool is held in the wellbore with cable 32 which is raised and lowered in the wellbore with a constant speed winch 33 and tripod 34. Information from the tool is transmitted to instrumentation and recording equipment 36. This recording equipment provides both analog real-time results and digitally recorded data. A weight 100 is used to keep the cable taut. Pre-installed metallic bands 101 can be used as depth markers/calibrators. It may be desirable to use separate cables for raising/lowering the tool and for transmitting data.

Greater detail regarding the construction of a first embodiment of the logging tool is provided in FIG. 15. To provide both high vertical resolution and deep probing depths, two banks of antennas are provided. The lower bank of antennas 37 is designed to give the best vertical resolution (approximately 2 inches) while probing a relatively shallow depth (approximately 1 inch). The three antennas (38, 39, and 40) are of the cavity-backed slot type having an aperture dimension of $1\frac{1}{8}'' \times \frac{1}{4}''$. The small dimensions of the aperture necessitates that the antenna cavity be partially filled with deionized water and then filled completely with a silicone rubber compound (Silastic TM 732 RTV adhesive/sealant made by Dow Corning). The return loss characteristics of the antennas result in an operating frequency of 1225 MHz.

In order to minimize direct coupling between the antennas via surface currents, the antennas are staggered so as to be arranged in a spiral fashion. The plane of polarization of the lower bank of antennas 37 is vertical.

The upper bank of antennas 42 is designed to give somewhat deeper probing depth (approximately 2 inches) at the sacrifice of some resolution. The two transmitting antennas, 43 and 44, are also the cavity backed, water/Silastic TM filled slot type, but have an aperture of $3\frac{1}{2}$ inches by $\frac{3}{4}$ inch, and are turned 90° with respect to the lower bank antennas. Thus, the plane of polarization of these antennas is horizontal. The orthogonality of polarization of the two antenna banks provides sufficient isolation between them if they were to be operated simultaneously.

In the upper bank the receiving antenna 45 differs from the transmitting antennas in that it is a slot in a metal sheet, backed by a cavity filled with deionized water and Silastic TM. The "long" dimension of this cavity is horizontal, thus permitting the two transmitting antennas to be in close proximity to each other ($5\frac{1}{2}$ inches).

"Choke" slots 46 and 47 are placed between the transmitting antennas and the receiving antenna to minimize direct coupling. These slots are filled with RT Duroid TM dielectric having a dielectric constant of approximately 10.

The return loss characteristics of the upper bank of antennas give rise to a common operating frequency 1100 MHz. Pressure arm 31 holds the tool in place in the well.

Internally, the logging tool includes RF source 48, variable attenuator 49, switches 50, 54 and 55, hybrid 51, amplifier 56 and receiver 57. The function of these devices is discussed in greater detail below.

FIG. 16 is an RF system block diagram for the tool in the first embodiment. The device consists of a 1-2 GHz microwave source 48 which transmits a signal through a variable attenuator 49. Switch 50 alternately transfers the microwave signal to the sum port 52 and the delta port 53 of the 180° hybrid, 51. Switches 54 and 55 alternately transfer the Σ and Δ signals to the upper bank 42 and lower bank 37 transmitting antennas.

Receiving antennas 39 and 45 send the received signal through switch 55 to 20 dB amplifier 56, and on to receiver 57. Appropriate cables are phase matched.

FIGS. 17a, b, and c show a second (preferred) embodiment of the logging tool. In this embodiment only a single bank of antennas consisting of a single transmitting antenna 60 and two receiving antennas 61 and 62 are provided. The antennas are identical and no longer have a staggered arrangement; their phase centers are placed along a vertical line. The decoupling between the transmitting and receiving antennas is achieved by placing choke slots 59 filled with radio frequency absorbing material between them. The spacing between the transmitting antenna 60 and the receiving antennas 61 and 62 is 1 inch and the path of propagation of radiation is reversed, i.e., there is a single transmitting antenna 60 and two receiving antennas 61 and 62. Three amplifiers/receivers 76 are utilized in this embodiment.

A third channel called the "mismatch" channel measures the power reflected from the transmitting antenna due to mismatch between the antenna and the formation/ casing combination.

A 15-Volt DC power source 74 and a 20-Volt power source 75 supply the electrical energy for the device.

An RF source 63, variable attenuator 64, hybrid 68, and rollers 80 are also provided. Information is transmitted to the surface via multiple conductor cable 77. In the second preferred embodiment the device is held in the well with pressure wheels 80 which provide a smoother tool traverse during logging. Directional coupler 65 is used to sample the power reflected back from the transmitting antenna, so as to provide a MISMATCH signal.

FIG. 18 provide an RF diagram for the second preferred embodiment. As shown, this device operates and records data simultaneously on all three channels on a continuous basis, removing the need for any switches. In this embodiment source 63 transmits a signal to variable attenuator 64 and through directional coupler 65 to transmitting antenna 60. Receiver 66 and amplifier 67 provide information regarding mismatch between the antenna and formation.

Signals received at the receiving antennas 61 and 62 are combined in a 180° hybrid 68 to generate the Σ and Δ signals, which are amplified in amplifiers 69 and 70 before being detected at the receivers 71 and 72. Note that in this embodiment the center antenna is a transmitter and the upper and lower antennas are receivers. The path of the radiation here is reversed from that described earlier, but achieves the same result.

As would be expected, actual well logs are often less than ideal and some degree of experience must be used in their interpretation. FIGS. 19 and 20 show well logs obtained with the above described tools.

In general, the primary emphasis in interpreting the well logs is on the delta channel. The sum and the mismatch channels provide additional information which is used to corroborate the delta channel results, especially in the event of ambiguities.

FIG. 19 shows a sample well log for a laboratory logging well using the second preferred embodiment. An 8-inch hydrocarbon layer was established at the 17 and 5-inch levels. The hydrocarbon/water interface (labeled as 78) in the log occurs at approximately $16\frac{1}{2}$ " (the middle of the two high delta peaks) and the hydrocarbon/ air interface (labeled as 79) occurs at $25\frac{1}{2}$ " indicating a very good correlation.

FIG. 20 shows a sample well log obtained with the second embodiment from an aquifer in Boise, Id. with a significant layer of gasoline on its surface. The formation is a coarse sand, cobbly formation. The log indicates delta peaks at hydrocarbon/water interface at the 2690.78' elevation and an air/hydrocarbon interface at 2691.31' elevation. The sum decreases from a high level to a lower level roughly corresponding to these peaks. The mismatch channel also changes levels corresponding to and supporting the delta peaks. The very large negative peaks on the mismatch channel are used to electronically mark elevations during the logging process.

By contrast to the well logging results, a standard monitoring well indicated the top of the hydrocarbon layer to be at 2690.50 feet and the bottom of the hydrocarbon layer to be at 2689.86 feet. Therefore, the hydrocarbon thickness with a standard monitoring well would be estimated to be 7.7 inches while the logging indicates the thickness to be 6.4 inches. This difference is substantial and would be significantly greater in formation with a less coarse formation.

FIG. 21 is a well log obtained in the same formation as that described in FIG. 21 in an area where no hydrocarbon is present on the water table. The delta peak for the water/air interface is observed at the 2694.56' elevation.

tion. The sum and mismatch shift to different values at this same elevation. No other distinctive delta peak is observed, and no support for considering any of the noise peaks as another delta interface is seen in the sum and mismatch channels.

The hydrocarbon layer detected by the tool in the above-described logs is the saturated hydrocarbon layer and its associated capillary fringe. (See the Van Dam article cited earlier and incorporated by reference). This information can be used to estimate the volume of hydrocarbon spilled to groundwater.

In all of the above well logs, log interpretation can be further simplified with curve smoothing techniques familiar to one skilled in the art.

The concept of null-balanced logging would also find utility in logging a typical crude oil production or exploratory well. The antenna for an open hole oil or gas well logging tool will be generally configured as shown above in the second preferred embodiment. However, in a crude oil production well it will be necessary to operate the device in an open hole environment since it will not be practical to utilize plastic casing and/or to maintain the hole in an air-filled condition. Therefore, the tool will be completely encased, water tight, and all internals will need to be designed for the temperature encountered in oil bearing strata. The antennas would be designed to operate efficiently when in direct contact with a lossy formation.

In addition, since the material surrounding the tool in an open hole will frequently be lossy (conductive), the sum, delta, and mismatch signals will be complex, i.e., they have both amplitude and phase components.

To account for those differences, phase discriminators are used in place of receivers. These devices give the phase and amplitude of an unknown signal in relation to a standard or reference signal.

The sum and delta signals may now be written as:

$$\Sigma^*(x) = \quad (7)$$

$$GM^*(x)[M^*(x+d)e^{ik^*(x+\frac{d}{2})d} + M^*(x-d)e^{ik^*(x-\frac{d}{2})d}]$$

$$\Delta^*(x) = \quad (8)$$

$$GM^*(x)[M^*(x+d)e^{ik^*(x+\frac{d}{2})d} - M^*(x-d)e^{ik^*(x-\frac{d}{2})d}]$$

where:

G = a "geometric spread" factor that can be determined empirically or from theoretical modeling as is done, for example, in the EPT tool.

*Indicates a complex quantity.

-continued

$k^*\left(x + \frac{d}{2}\right) =$	wave vector for the region between the transmitting antenna and the top receiving antenna.
$k^*\left(x - \frac{d}{2}\right) =$	wave vector for the region between the transmitting antenna and the bottom receiving antenna.
$k^* =$	a function of the dielectric constant and the conductivity.
$M^*(x) =$	factor arising from mismatch between the transmitting antenna and formation
$M^*(x+d) =$	factor arising from mismatch between the top receiving antenna and formation
$M^*(x-d) =$	factor arising from mismatch between the bottom receiving antenna and formation.

Information about $M^*(x)$ is recorded by the mismatch channel when the tool is at location x . Information about $M^*(x-d)$ has been recorded when the tool was at the location $(x-d)$. Similarly, $M(x+d)$ will become $M^*(x)$ when the tool is moved upward, a distance of d . Note that $M^*(x-d)$ and $M^*(x+d)$ refer to the receiving antennas but these quantities can be determined for the transmitting antenna since all three antennas are identical. Therefore, the quantities $M^*(x)$, $M^*(x-d)$ and $M^*(x+d)$ are known.

Adding and subtracting equations 7 and 8, it is found:

$$\Sigma^*(x) + \Delta^*(x) = 2GM^*(x)M^*(x+d)e^{ik^*\left(x+\frac{d}{2}\right)d} \quad (9)$$

$$\Sigma^*(x) - \Delta^*(x) = 2GM^*(x)M^*(x-d)e^{ik^*\left(x-\frac{d}{2}\right)d} \quad (10)$$

$$\text{Solving for } k^*\left(x + \frac{d}{2}\right) \text{ and } k^*\left(x - \frac{d}{2}\right) \quad (11)$$

$$k^*\left(x + \frac{d}{2}\right) = \frac{1}{id} \ln \left\{ \frac{\Sigma^*(x) + \Delta^*(x)}{2GM^*(x)M^*(x+d)} \right\}$$

$$k^*\left(x - \frac{d}{2}\right) = \frac{1}{id} \ln \left\{ \frac{\Sigma^*(x) - \Delta^*(x)}{2GM^*(x)M^*(x-d)} \right\} \quad (12)$$

Since all of the quantities on the right side are known for the sum, delta, and mismatch channels $k^*(x+d/2)$ and $k^*(x-d/2)$ can be determined. From these the dielectric constants and the conductivities for the regions between the transmitting antenna and each of the receiving antennas can be found using simple relations known to one skilled in the art.

As a tool travels in the well, the coupling between an antenna and the formation changes continuously because of changing formation conditions, thickness of the mudcake layer and/or rugosity of the borehole wall. The prior art tools seek to eliminate this unknown quantity by taking the ratio of the measurements made by two adjacent receiving antennas. This assumes that the two receiving antennas at a given time have the same coupling. This assumption may or may not be true, but in any event, we have no way of knowing if it is true or not for a given formation. In our tool we actually measure this mismatch, and take this into account in a direct

fashion. Besides alleviating the above problem, the mismatch channel can also tell us about the borehole rugosity and the mudcake condition (qualitatively).

FIGS. 22a, b, and c illustrate the tool that would be used in the open hole application discussed above. The tool comprises of a body 81, antenna pad 82, and pressure arm 83. The antenna configuration is similar to the second preferred embodiment and includes receiving antennas 84 and 85 and transmitting antenna 86. Again, choke slots 87 are provided. Internally, the device includes power sources 88 and 89, and RF source 90. Also included in the device are the following (which are discussed in greater detail below): variable attenuator 91, power sampler 92, 3-way power divider 93, amplifiers 94, and phase discriminators 95, 96, and 97. Hybrid 98 and directional coupler 99 perform the same function as discussed in relation to the first and second preferred embodiments.

FIG. 23 shows an RF block diagram for the third preferred embodiment. FIG. 23 is best described by following the electromagnetic signal along its path. The source 88 emits a continuous-wave (CW) electromagnetic signal which passes through a forward directional coupler 92. Here, a small portion of the power is sampled off to a three-way power-divider 93 which will serve to provide three reference signals.

The main signal is then fed to a variable attenuator 91 and on through a directional coupler 99 to the transmitting antenna 86. The attenuator 91 serves to continually adjust the transmitted power depending on the nature of the formation encountered, and can be automatically controlled by a feedback loop that also samples the received power at the receiving antennas 84 and 85.

Of the power that is incident at the terminal of the transmitting antenna 86, a portion is reflected back because of mismatch between this antenna and the formation opposite it. This reflected power is sampled by the directional coupler 99, amplified in the amplifier 94a and fed to a phase discriminator 95 which also receives a reference signal from the power divider 93 upon being amplified in the amplifier 94b. The d.c. outputs of the phase discriminator 95 contain information about the phase and amplitude of the mismatch signal.

Of the energy that leaves the transmitting antenna and enters the formation, portions are received by the receiving antennas 84 and 85. These signals are combined in a 180° hybrid 98. The outputs of this hybrid are the sum and the difference of the two input signals.

The difference signal is amplified in an amplifier 94c and fed to a second phase discriminator 96 which also receives a reference signal from the power divider 93 upon being amplified in amplifier 94d. The d.c. outputs of the phase discriminator 96 contain information about the phase and amplitude of the delta channel signal.

The sum signal is likewise amplified in the amplifier 94e and fed to a third phase discriminator 97 which also receives a reference signal from the power divider 93 upon being amplified in amplifier 94f. The d.c. outputs of the phase discriminator 97 contain information about the phase and amplitude of the sum channel signal. In FIG. 23 the cables are adjusted to have the correct electrical lengths.

FIG. 24 illustrates a numerically generated well log for the third embodiment. This sample well log assumes the tool is operating at 1000 MHz and the thickness of the oil sand is 10 inches. The distance between the receiving antennas and transmitting antenna is assumed to be 2 inches. The porosity, water saturation (S_w), and oil

saturation (S_o) for the three zones is shown on the Figure. The water resistivity is assumed to be 0.2 ohm-meters. As with the first two embodiments, the delta channel (here, especially the phase signal) shows a clear shift at each interface. Support for interpreting these shifts as an interface is found in the remaining channels.

FIG. 25 illustrates the use of an additional parameter which can aid in the use of the third embodiment. In this Figure, the formation and tool are the same as shown in FIG. 24. The plotted parameter, however, is "omega" (X). This empirical parameter is defined by: $X = (\text{Sum Channel amplitude}) [\cos (\text{delta channel phase})]$. As shown, this parameter shows a sharp delineation at the oil/water contact.

The frequency of operation of any of the above-described embodiments should preferably be such that the distance between the transmitting and receiving antennas is less than one-half the effective wavelength of the radiation. For a given tool spacing, this establishes an upper limit to the operating frequency. An approximate lower limit of the operating frequency is obtained from the consideration of resolution distance. If we wish to resolve a distance down to the spacing from the transmit to receive antenna, then this distance must be greater than approximately one-third the effective wavelength. In this way we bracket the range of operating frequencies. In typical application, this range will be approximately 1000-1500 MHz.

In the groundwater application, the tool should be operated near the top of this range, to maximize resolution. In an openhole, the tool should be operated near the bottom of the range, in order to maximize the depth of investigation. Obviously, the operating frequency can readily be varied and the optimum frequency for a given application can readily be determined by one skilled in the art.

While the above embodiments have been described with a great deal of specificity it is to be understood that the scope of the invention is not to be limited thereto, but instead should be limited only by the appended claims, along with the full scope of equivalents thereto.

What is claimed is:

1. A method of determining the location of an interface of dielectrically different material comprising the steps of:

- (a) transmitting electromagnetic radiation from a first transmitting antenna and a second transmitting antenna in a wellbore, the radiation from the first transmitting antenna and the second transmitting antenna having a common phase and amplitude, said first transmitting antenna located above said second transmitting antenna;
- (b) receiving a sum signal resultant from the step (a) at a receiving antenna located between said first transmitting antenna and said second transmitting antenna;
- (c) transmitting electromagnetic radiation from the first transmitting and the second transmitting antennas, the transmitted radiation from the first and second antennas having a common amplitude and phases differing by 180°;
- (d) receiving a delta signal resultant from step (c) at said receiving antenna;
- (e) moving said antennas across the interface; and
- (f) monitoring said sum and said delta signals for changes whereby the interface can be detected.

2. A method of determining the location of an interface of dielectrically different materials comprising the steps of:

- (a) transmitting electromagnetic radiation from a transmitting antenna;
- (b) receiving said electromagnetic radiation at a first receiving antenna located above said transmitting antenna to produce a first signal;
- (c) receiving said electromagnetic radiation at a second receiving antenna located below said receiving antenna to produce a second signal;
- (d) adding said first and second signals to create a sum signal;
- (e) Phase shifting said first signal from said second signal a total 180° to produce phase shifted signals;
- (f) adding said phase shifted signals to create a delta signal;
- (g) moving said antennas across the interface; and
- (h) monitoring said sum and said delta signals for changes whereby the interface can be located.

3. The method as recited in claim 1 or 2 wherein said dielectrically dissimilar materials are hydrocarbons and air.

4. The method as recited in claim 1 or 2 wherein the dielectrically dissimilar materials are a hydrocarbon in a groundwater formation and air.

5. The method as recited in claim 1 or 2 wherein the transmitting and receiving steps are performed on a pad-type device.

6. An electromagnetic logging tool for determining the location of a hydrocarbon-bearing formation comprising:

- (a) an uncased well;
- (b) an enclosed logging tool, said logging tool further comprising:
 - (i) an electromagnetic transmitting antenna;
 - (ii) a first receiving antenna above said transmitting antenna;
 - (iii) a second receiving antenna below said transmitting antennas;
 - (iv) means for holding said antennas against a wall of said well;
 - (v) means for phase shifting signals received by said first and said second antennas by substantially 180° to produce offset signals and means for combining said offset signals to produce a delta signal;
 - (vi) means for measuring reflected signals due to impedance mismatch between the antenna and formation to produce a mismatch signal;
 - (vii) means for producing reference signals of stable phase and amplitude;
 - (viii) phase discriminator means for comparing the reference signals to the delta signal and mismatch signal to determine their phase and amplitude;
- (c) means for providing said logging tool in said well, and;
- (d) means for monitoring the phase and amplitude of delta signal and the mismatch signal for changes whereby properties of the formation can be measured.

7. The method as recited in claim 5 wherein the frequency of said electromagnetic radiation is substantially in the range from 1000 to 1500 MHz.

8. The method as recited in claim 5 wherein the frequency of said electromagnetic radiation is substantially 1500 MHz.

9. The method as recited in claim 4 further comprises the step of locating a hydrocarbon/water interface.

10. The method as recited in claim 1 or 2 wherein said transmitting and receiving steps are performed adjacent to a nonmetallic casing, said plastic casing defining an air-filled well.

11. The method as recited in claim 1 or 2 further comprising the step of measuring power reflected from the material back into at least one transmitting antenna using a directional coupler attached to a power monitor.

12. Apparatus for determining the location of an interface of dielectrically dissimilar materials comprising:

- (a) a first radiation transmitting means;
- (b) a second radiation transmitting means, said second radiation transmitting means alternately transmitting radiation of the same phase as said first radiation transmitting means and transmitting radiation 180° out of phase from said first radiation transmitting means;
- (c) radiation receiving means located between said first and said second transmitting means for producing a received signal;
- (d) means for moving the apparatus across the interface; and
- (e) means for monitoring said received signal for changes as the apparatus is moved across the interface whereby the interface can be located.

13. Apparatus for determining the location of an interface of dielectrically dissimilar materials comprising:

- (a) a radiation transmitting antenna;
- (b) a first receiving antenna vertically displaced from said transmitting antenna;
- (c) a second radiation receiving antenna vertically displaced from said transmitting antenna opposite said first receiving antenna;
- (d) means for phase shifting and combining a signal from said first and said second receiving antennas to produce a delta signal; and
- (e) means for monitoring the delta signal for changes whereby the interface can be located.

14. Apparatus as recited in claim 13 further comprising means for adding a signal from said first and said second receiving antenna prior to phase shifting to produce a sum signal and means for monitoring the sum signal.

15. Apparatus as recited in claim 12 or 13 further comprising a pad, said pad coinciding with the inside of a wellbore and holding said transmitting and receiving antennas.

16. A method for determining the location of an interface in a petroleum formation comprising the steps of:

- (a) inserting a logging tool into an uncased well at a first location;
- (b) transmitting electromagnetic radiation from a transmitting antenna on said logging tool;
- (c) receiving a first signal at a first receiving antenna located above said transmitting antenna;
- (d) receiving a second signal at a second receiving antenna located below said transmitting antenna;
- (e) phase shifting signals received by said first and said second signals substantially 180° to produce offset signals;
- (f) combining said offset signals to produce a delta signal;
- (g) moving said logging tool to a second location; and
- (h) monitoring a phase of said delta signal for changes as said tool is moved whereby said interface location can be determined.

17. Apparatus as recited in claim 15 wherein said transmitting and said receiving antennas are adapted to operate substantially in the frequency range from 1000 to 1500 MHz.

18. Apparatus as recited in claim 15 wherein said transmitting and receiving antennas are adapted to operate at a frequency of substantially 1500 MHz.

19. Apparatus as recited in claim 12 or 13 further comprising means to monitor power reflected from said transmitting antennas.

20. Apparatus as recited in claim 12 or 13 further comprising an air-filled, plastic cased well, said well adapted to receive said antennas.

21. Apparatus as recited in claim 20 wherein said well is drilled substantially into a groundwater formation.

22. Apparatus as recited in claim 12 or 13 wherein said means for moving is a winch connected to said apparatus via a cable.

23. Apparatus as recited in claim 12 or 13 further comprising a second bank of antennas, said second bank of antennas in closer proximity to each other than said first bank of antennas to give increased vertical resolution.

24. Apparatus as recited in claim 12 or 13 wherein said antennas are cavity backed slot antennas impedance-matched to transmit through a nonmetallic casing.

25. Apparatus as recited in claim 24 wherein said cavity back slotted antennas are filled materials selected from the group (a) with a silicone rubber compound and deionized water and (b) ceramic barium titanate chips and epoxy.

26. Apparatus as recited in claim 12 or 13 wherein said antennas are staggered in a spiral fashion.

27. Apparatus as recited in claim 12 wherein a long dimension of said receiving antenna is horizontal.

28. Apparatus as recited in claim 12 or 13 further comprising choke slots between said antennas.

29. Apparatus as recited in claim 28 wherein said choke slots are filled with a dielectric material.

30. Apparatus as recited in claim 12 or 13 wherein said antennas have their phase centers placed along a vertical line.

31. Apparatus as recited in claim 30 further comprising choke slots between said antennas.

32. Apparatus for determining the thickness of a hydrocarbon on a water table comprising:

(a) a surveillance well, said surveillance well being an air-filled, nonmetallic cased well inserted into said water table;

(b) a logging tool, said logging tool further comprising:

(i) a first antenna bank, said first antenna bank further comprising: a transmitting antenna; a first receiving antenna; and a second receiving antenna;

(ii) a source of electromagnetic radiation operably connected to said transmitting antenna;

(iii) a 180° hybrid, said 180° hybrid arranged to offset signals received by said first receiving antenna and said second receiving antenna by 180° to produce

offset signals and to combine said offset signals to produce a delta signal;

(c) means for recording said delta signal operably connected to said hybrid; and

(d) means for moving said logging tool in said well.

33. Apparatus as recited in claim 32 further comprising a gravel pack surrounding said cased well.

34. Apparatus as recited in claim 32 further comprising a second bank of antennas on said logging tool, said second bank of antennas spaced to provide high resolution.

35. Apparatus as recited in claim 32 wherein said first receiving antenna and said second receiving antenna and said transmitting antenna are a cavity partially filled with water and a silicone rubber compound.

36. Apparatus as recited in claim 32 wherein said first bank of antennas is a staggered bank antennas.

37. Apparatus as recited in claim 32 wherein said nonmetallic cased well is a polyvinyl chloride cased well.

38. Apparatus as recited in claim 32 further comprising choke slots in said first antenna bank between said antennas.

39. Apparatus as recited in claim 38 wherein said choke slots are filled with a dielectric material.

40. Apparatus as recited in claim 32 wherein said first antenna bank has its phase centers along a vertical line.

41. Apparatus as recited in claim 32 wherein said antennas are staggered in a signal fashion.

42. Apparatus as recited in claim 32 further comprising a winch connected to said logging tool to raise said logging tool.

43. Apparatus as recited in claim 32 further comprising means to monitor power reflected from material surrounding said casing into said transmitting antenna.

44. Apparatus as recited in claim 32 further comprising a pad, said pad containing said first antenna bank and adapted to substantially coincide to the inside of said surveillance well.

45. A method of determining the thickness of a hydrocarbon layer on a groundwater table comprising the steps of:

(a) installing an air filled nonmetallic well casing in a wellbore, said wellbore traversing the hydrocarbon layer on the groundwater;

(b) transmitting electromagnetic radiation from the well with a transmitting antenna;

(c) receiving the electromagnetic radiation in the well with a receiving antenna;

(d) moving the transmitting antenna and the receiving antenna in the well casing traversing through the hydrocarbon layer on the groundwater; and

(e) monitoring radiation received by the receiving antenna for phase changes whereby the thickness of the hydrocarbon layer can be determined.

46. Apparatus as recited in claim 44 wherein said antennas are adapted to operate in the frequency range from 1100 to 1500 MHz.

47. Apparatus as recited in claim 44 wherein said antennas are adapted to operate at a frequency of substantially 1500 MHz.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 4,831,331
DATED : May 16, 1989
INVENTOR(S) : Bibhas R. De et al

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Claim 2, Col. 15, line 12, "(d) adding said first and second"
should read --(d) adding said first
and said second--.

Claim 2, Col. 15, line 15, "a total 180°" should read --a total of
180°--.

Claim 5, Col. 15, line 27, "1 or 2 Wherein" should read --1 or 2
wherein--.

Claim 6, Col. 15, line 55, "(c) means for providing said" should
read --means for moving said--.

Claim 16, Col. 16, line 63, "((f)" should read -- (f) --.

Claim 41, Col. 18, line 29, "signal fashion" should read
--spiral fashion--.

Signed and Sealed this
Twenty-seventh Day of February, 1990

Attest:

JEFFREY M. SAMUELS

Attesting Officer

Acting Commissioner of Patents and Trademarks

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JEFFREY M. SAMUELS

Attesting Officer

Acting Commissioner of Patents and Trademarks



US005146086A

United States Patent [19]

De et al.

[11] Patent Number: 5,146,086

[45] Date of Patent: Sep. 8, 1992

[54] METHOD AND APPARATUS FOR IMAGING POROUS MEDIA AND METHOD FOR FABRICATING NOVEL OPTICAL MATERIALS

[75] Inventors: Bibhas R. De, Laguna Beach; Michael A. Nelson, Glen Avon; Kiran K. Pande, Laguna Hills, all of Calif.

[73] Assignee: Chevron Research and Technology Company, San Francisco, Calif.

[21] Appl. No.: 672,194

[22] Filed: Mar. 19, 1991

[51] Int. Cl.⁵ G01N 21/35

[52] U.S. Cl. 250/253; 250/256

[58] Field of Search 250/253, 255, 256; 73/38

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Primary Examiner—Janice A. Howell

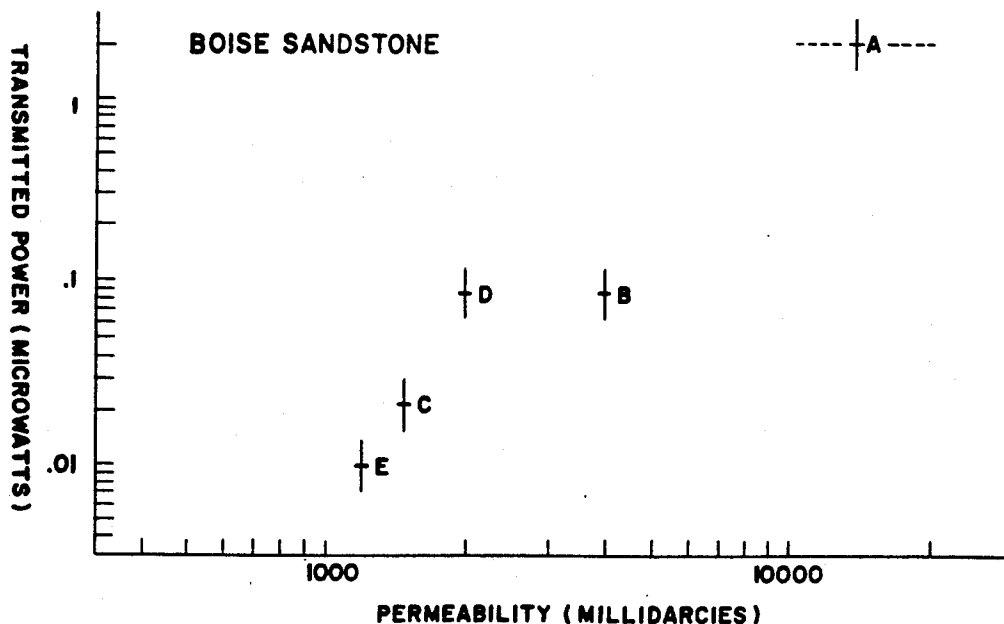
Assistant Examiner—Richard Hanig

Attorney, Agent, or Firm—Edward J. Keeling; David J. Power

[57] ABSTRACT

A method and apparatus is described for determining petrophysical properties of porous media by the use of light transmission through the media. Specifically, by using a highly collimated light source, preferably a laser, the permeability, grain size, wettability, porosity and clay swelling behavior of a sample can be determined on the scale of millimeters. A calibration curve or function is first established to correlate light transmission through a slab of sandstone on the order of 5 to 10 mm under known conditions. This curve is then used to determine unknown conditions by measuring light transmission and comparing the values to those on the curve. Other applications for the phenomenon of light transmission through porous media are disclosed whereby conditions in a flowing stream of liquid can be monitored by use of light transmission. Specifically, changes in the refractive index and immiscible contamination can be detected. Finally, the phenomenon described can be used to model subterranean hydrocarbon bearing reservoirs, particularly fluid flow at different points in the reservoir, using light rather than hydraulic flows to simulate fluid flow patterns.

19 Claims, 13 Drawing Sheets



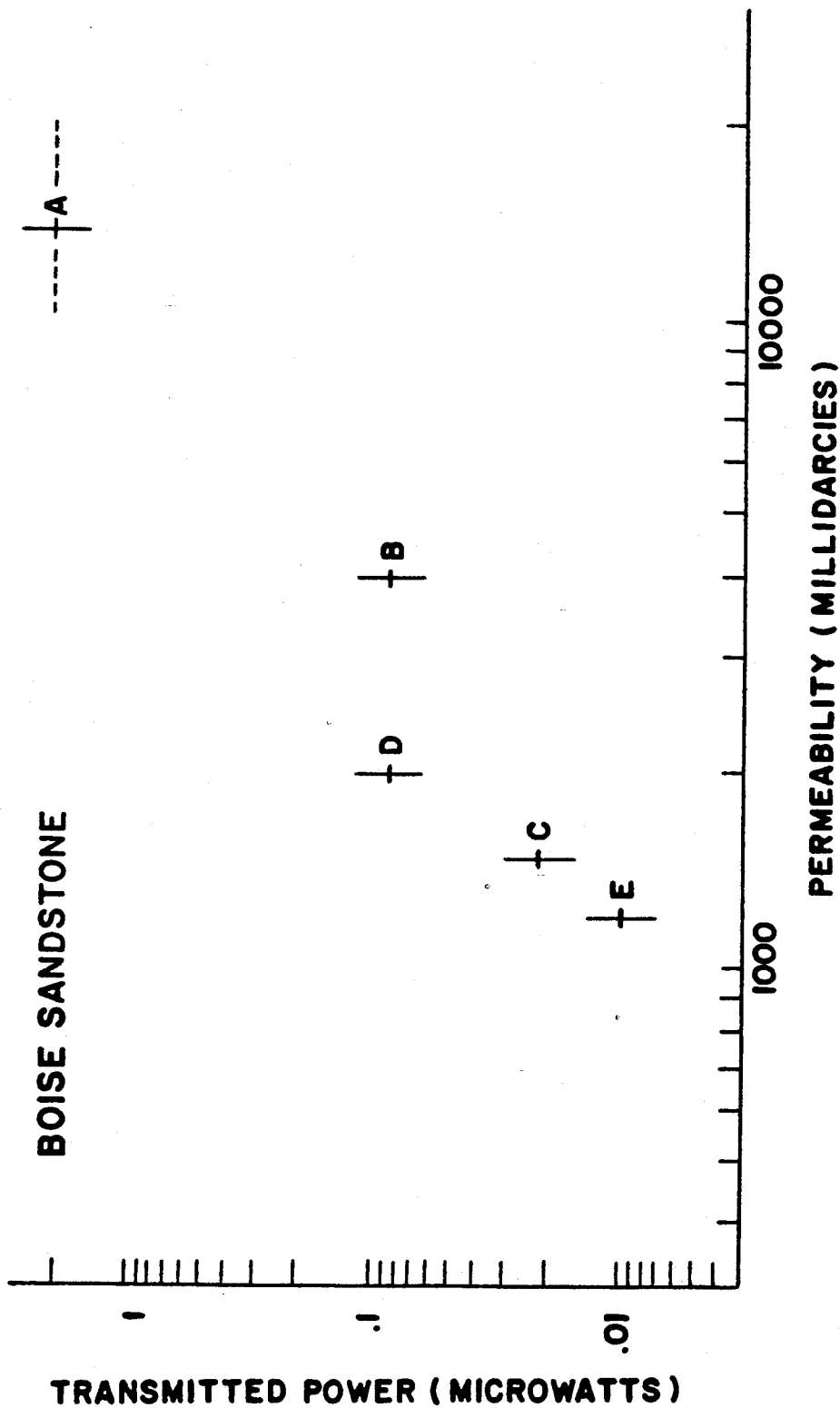
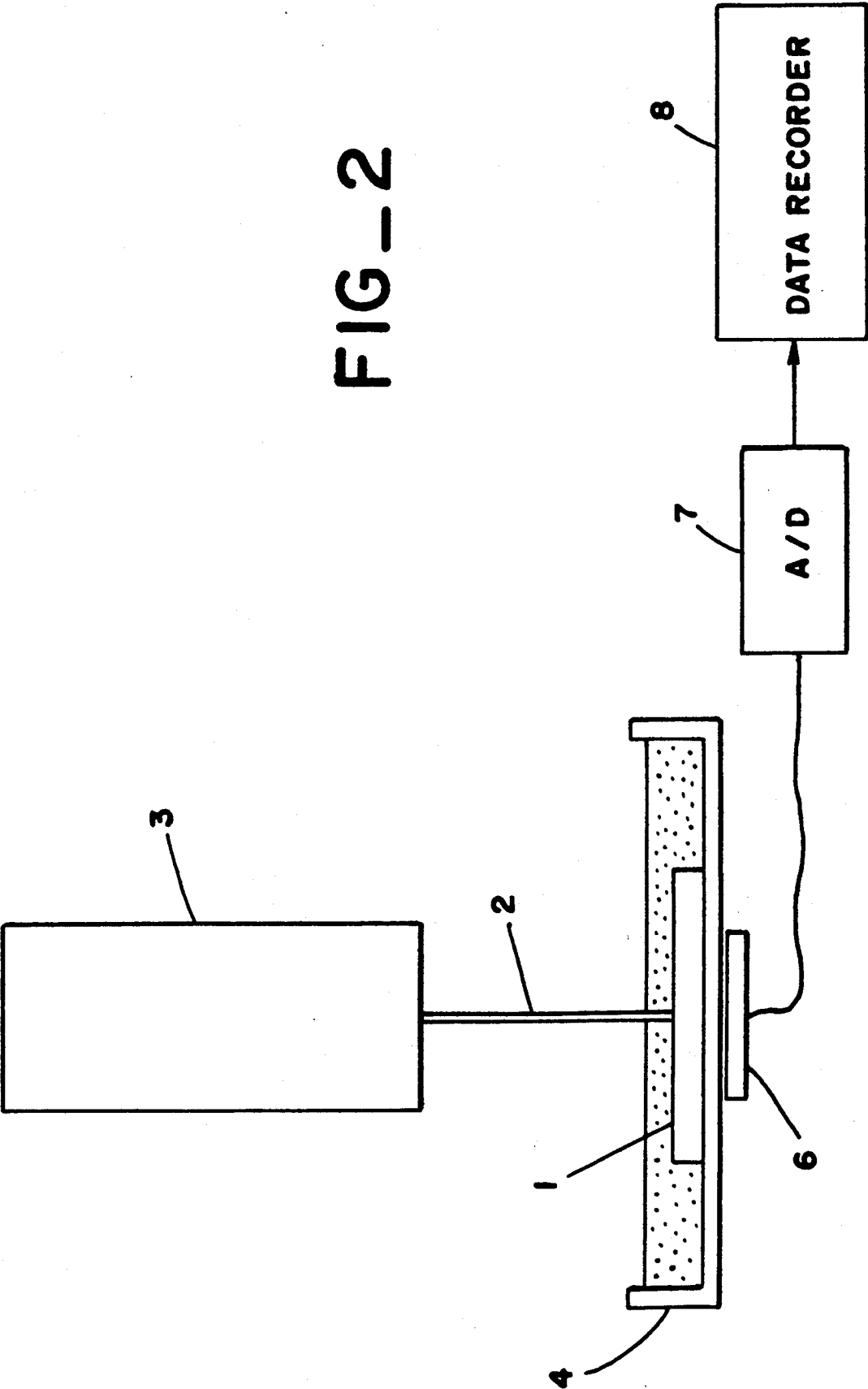


FIG-1

FIG-2



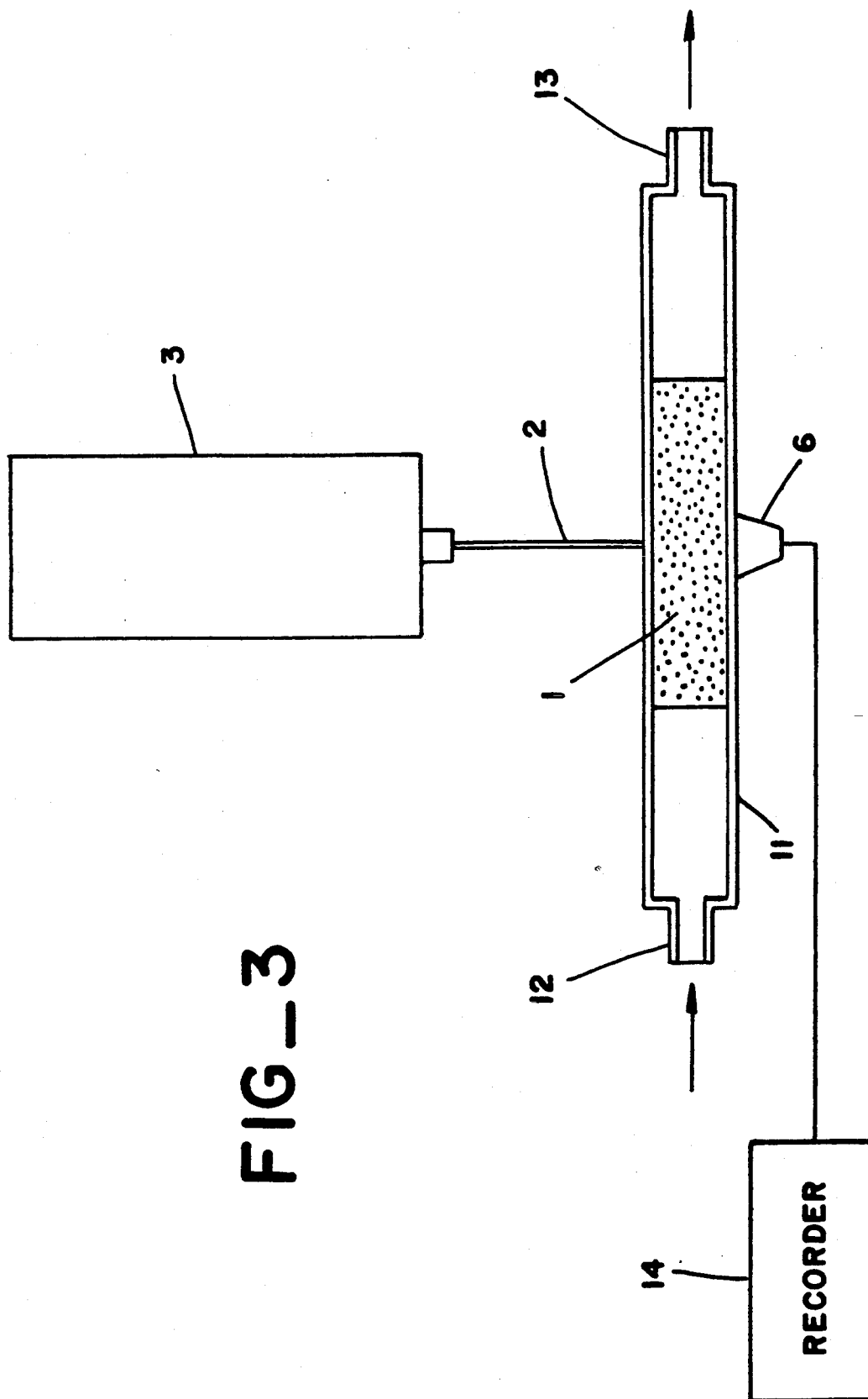
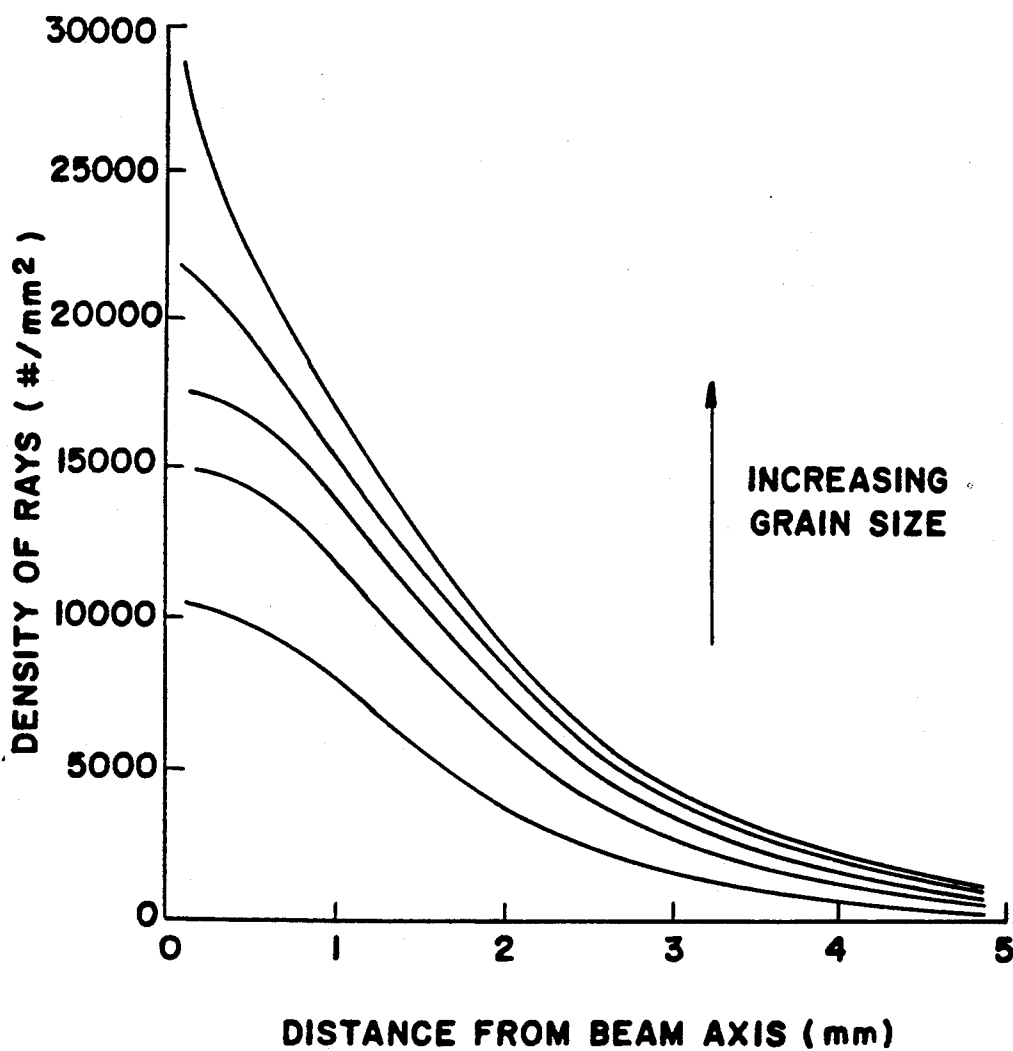


FIG-3

WATER SATURATED SAND PACK**FIG_4**

WIDTH OF EMERGENT BEAM FROM
COMPOSITE POROUS MEDIUM AS A FUNCTION
OF GRAIN SIZE OF THE MEDIUM

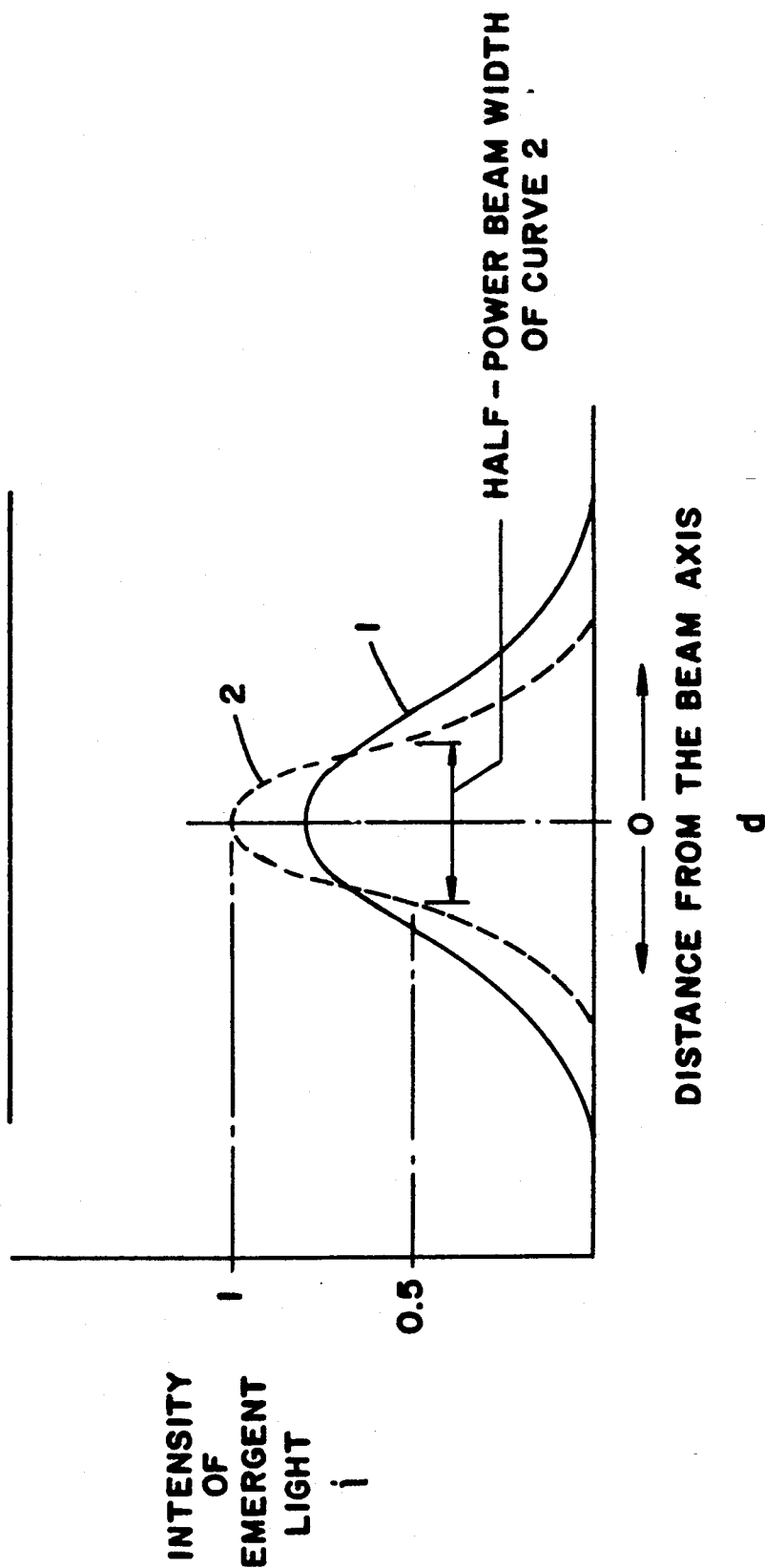
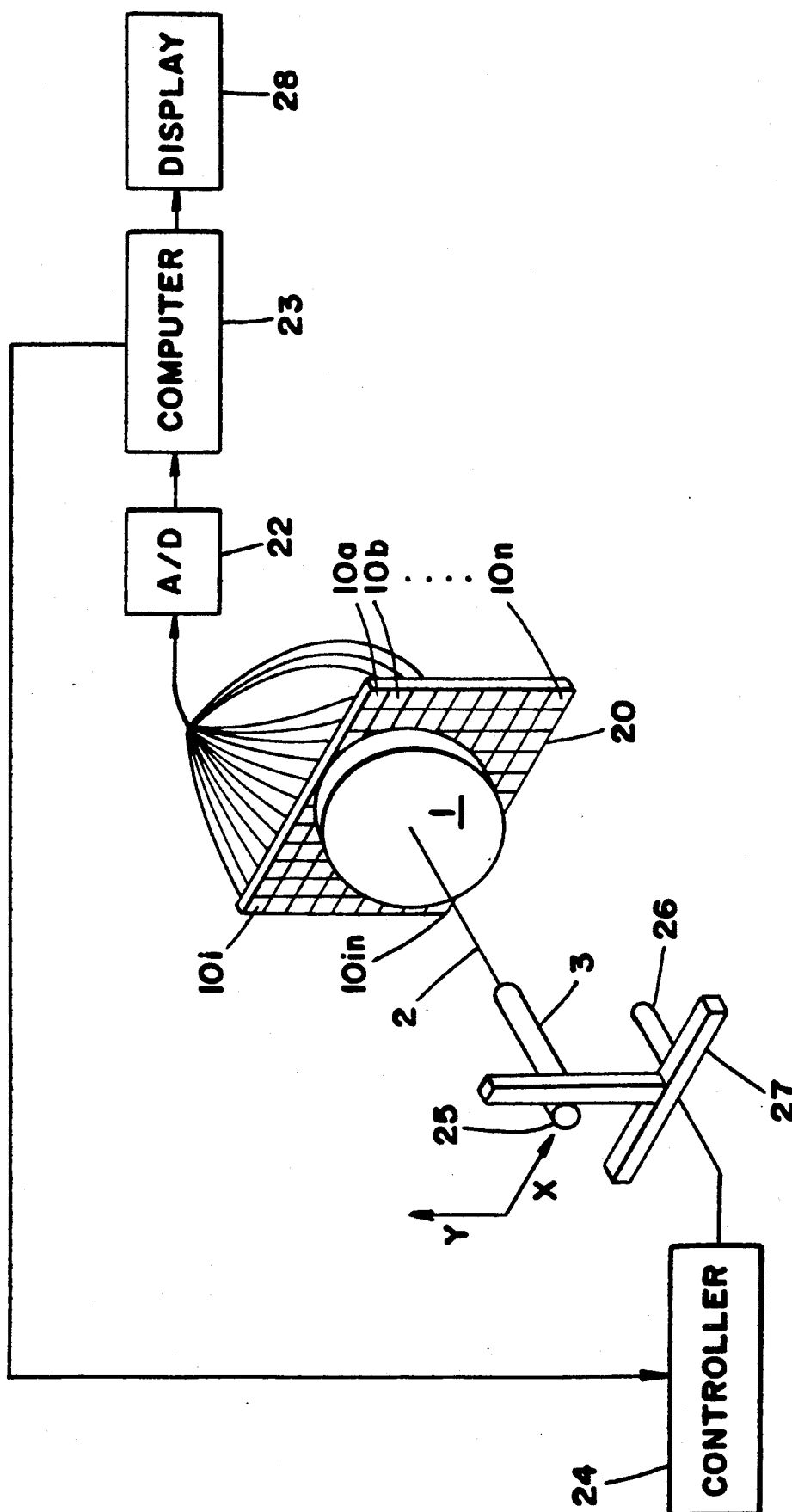
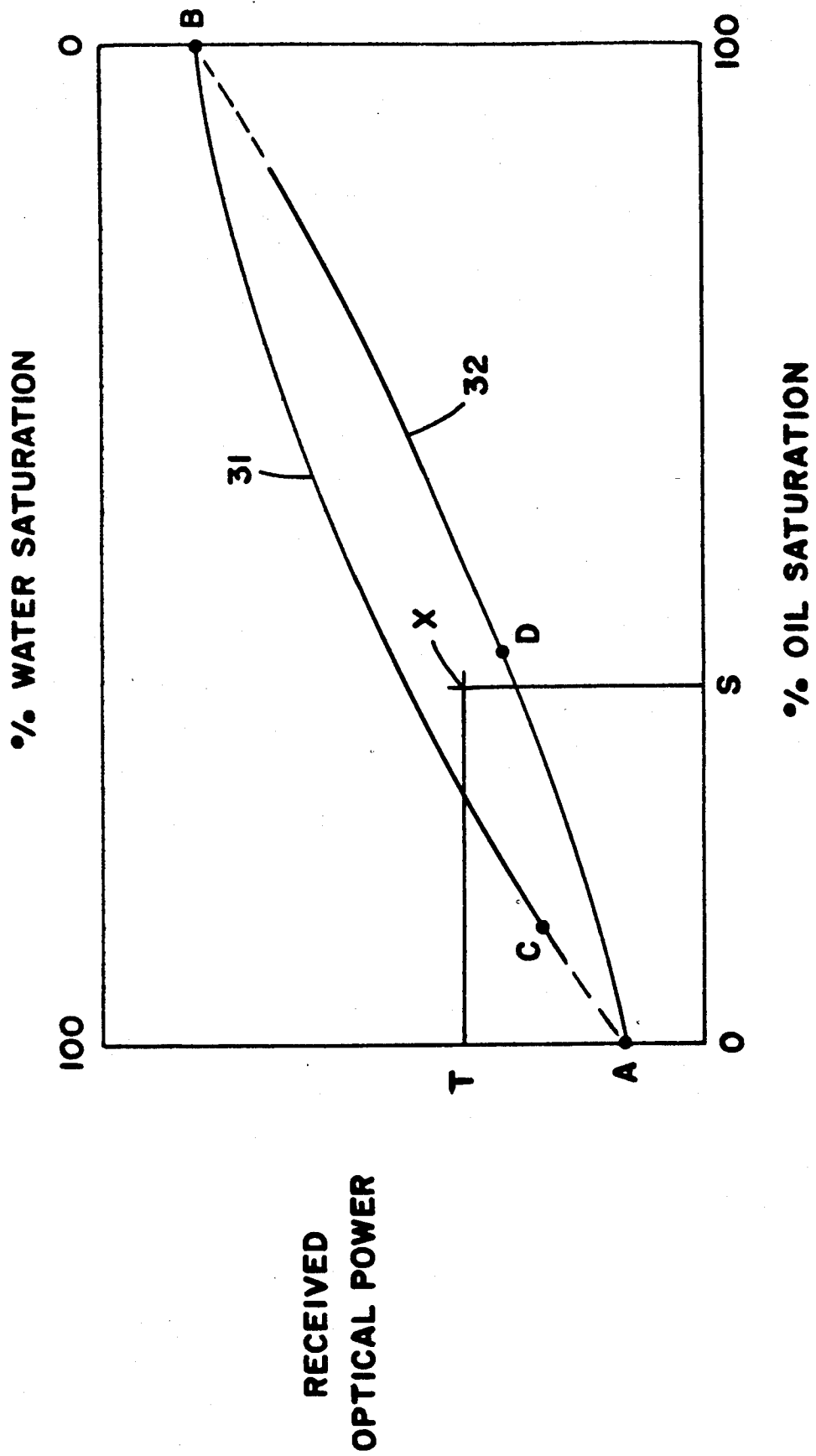
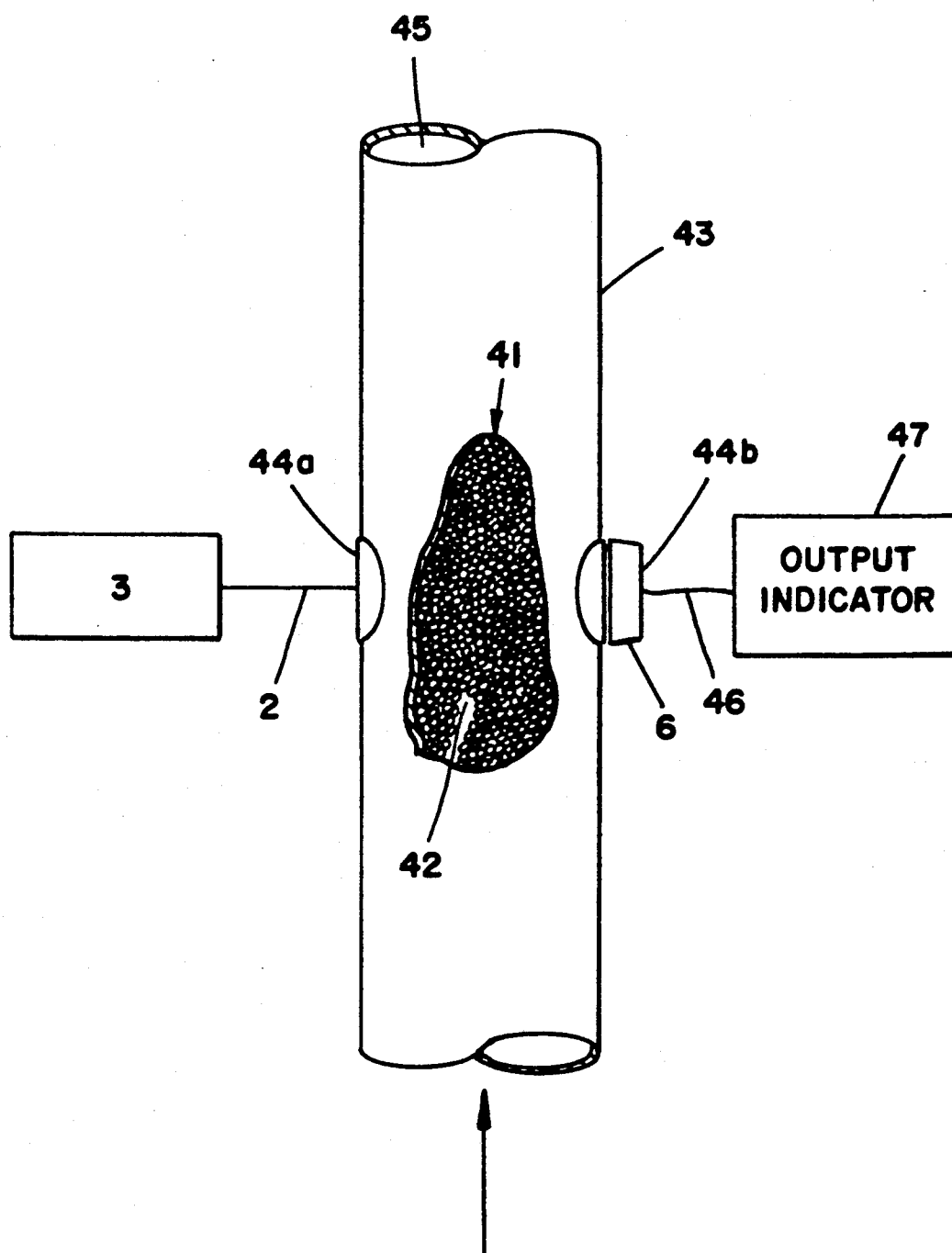


FIG-5

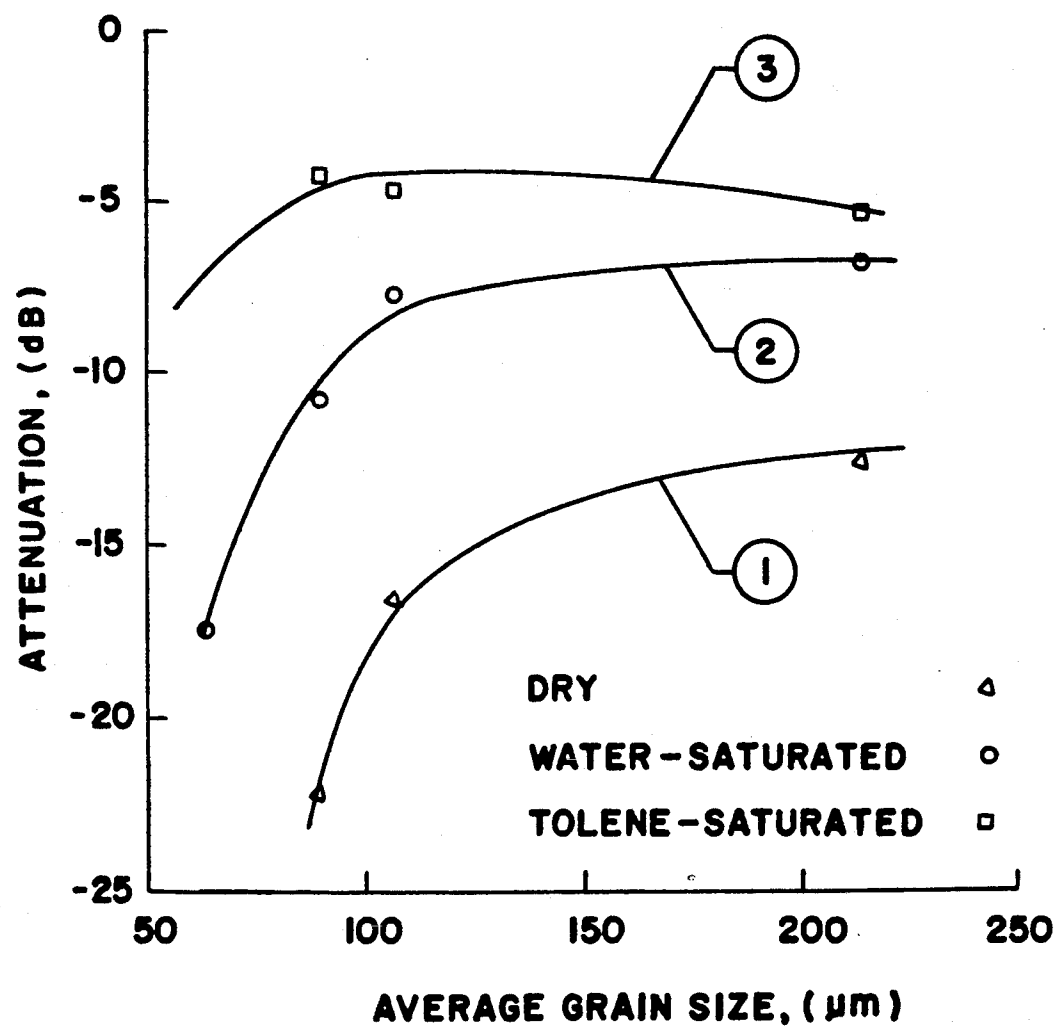


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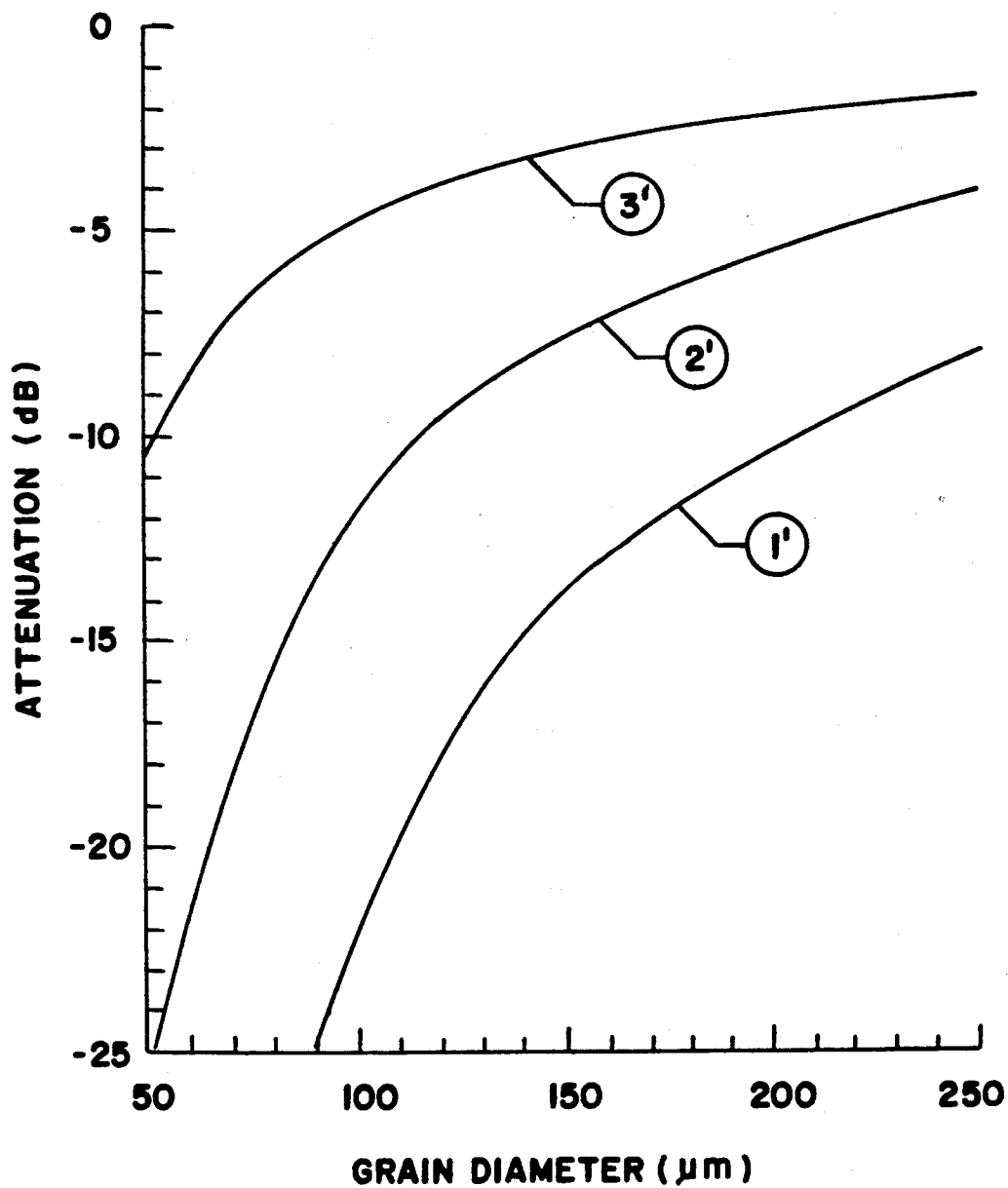


FIG_8

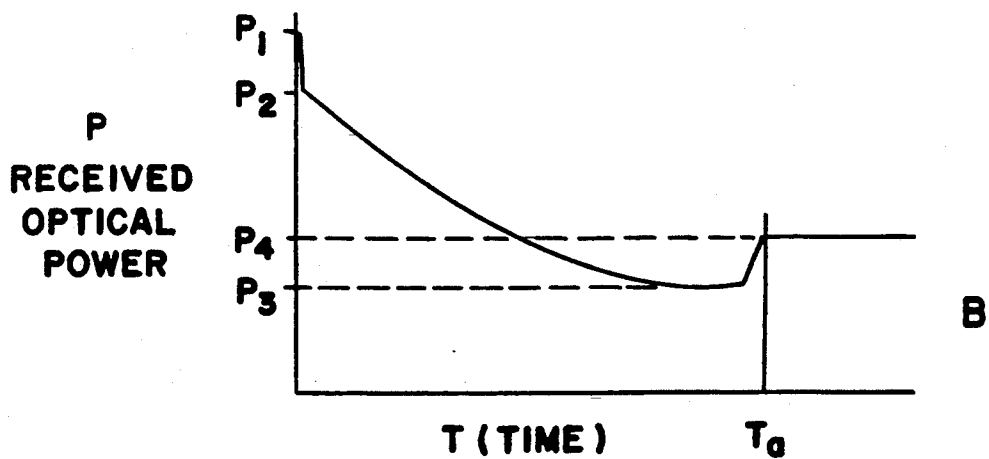
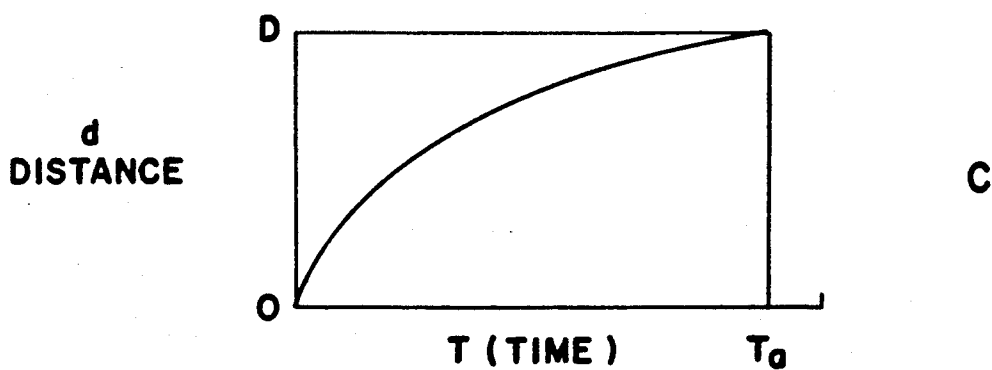
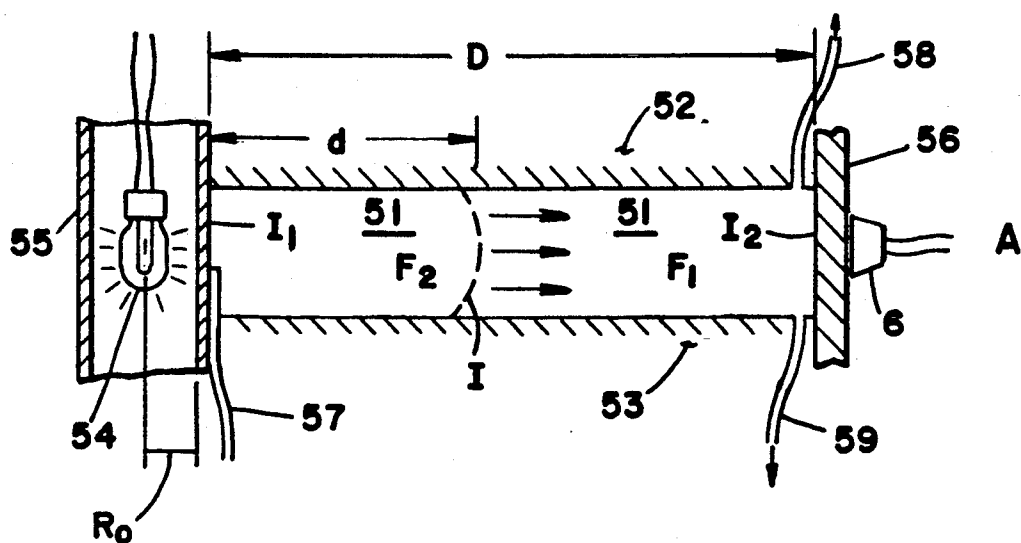


FIG_9

QUARTZ GRAINS; 3-D RANDOM SIMULATION



FIG_10



FIG_11

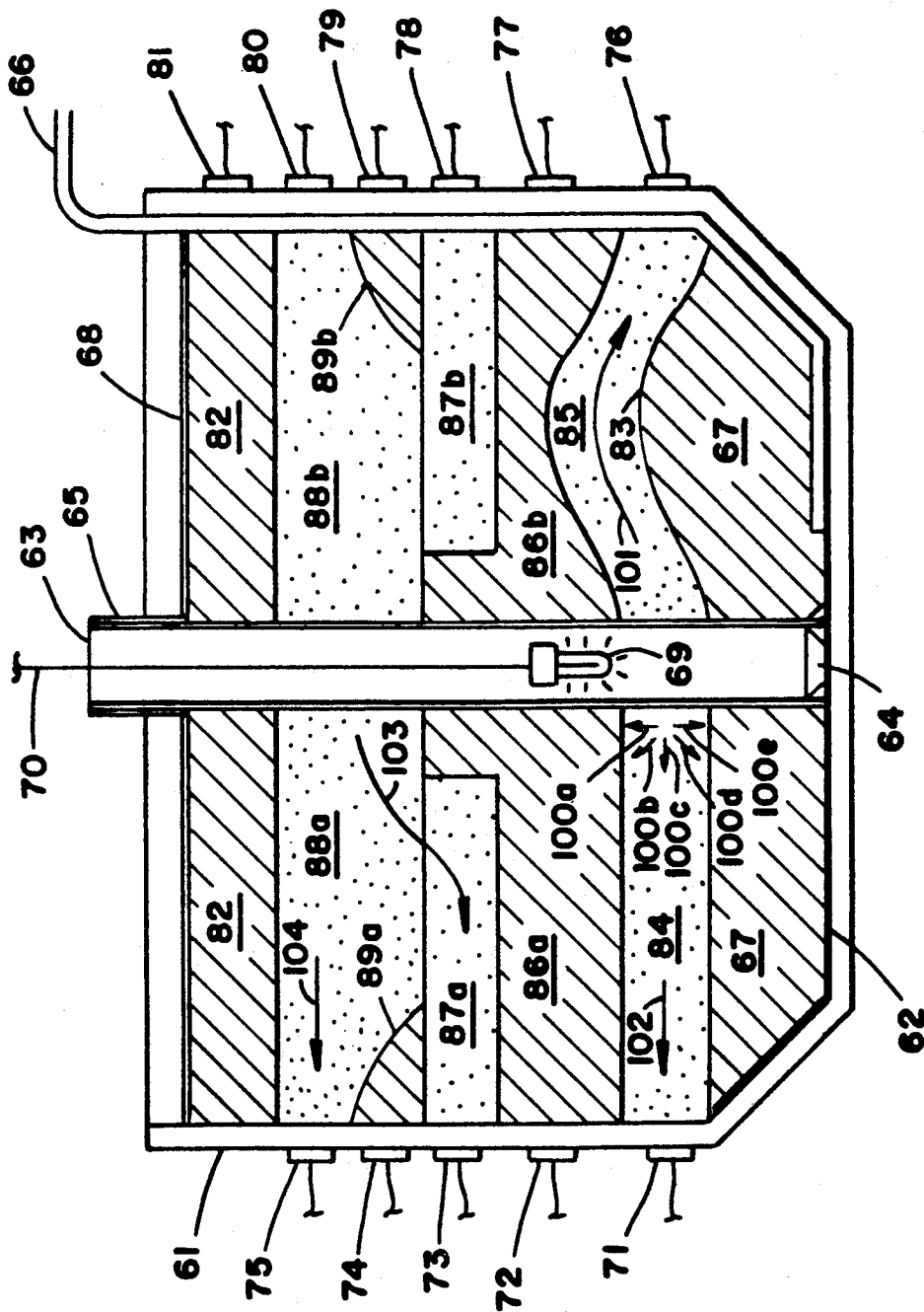
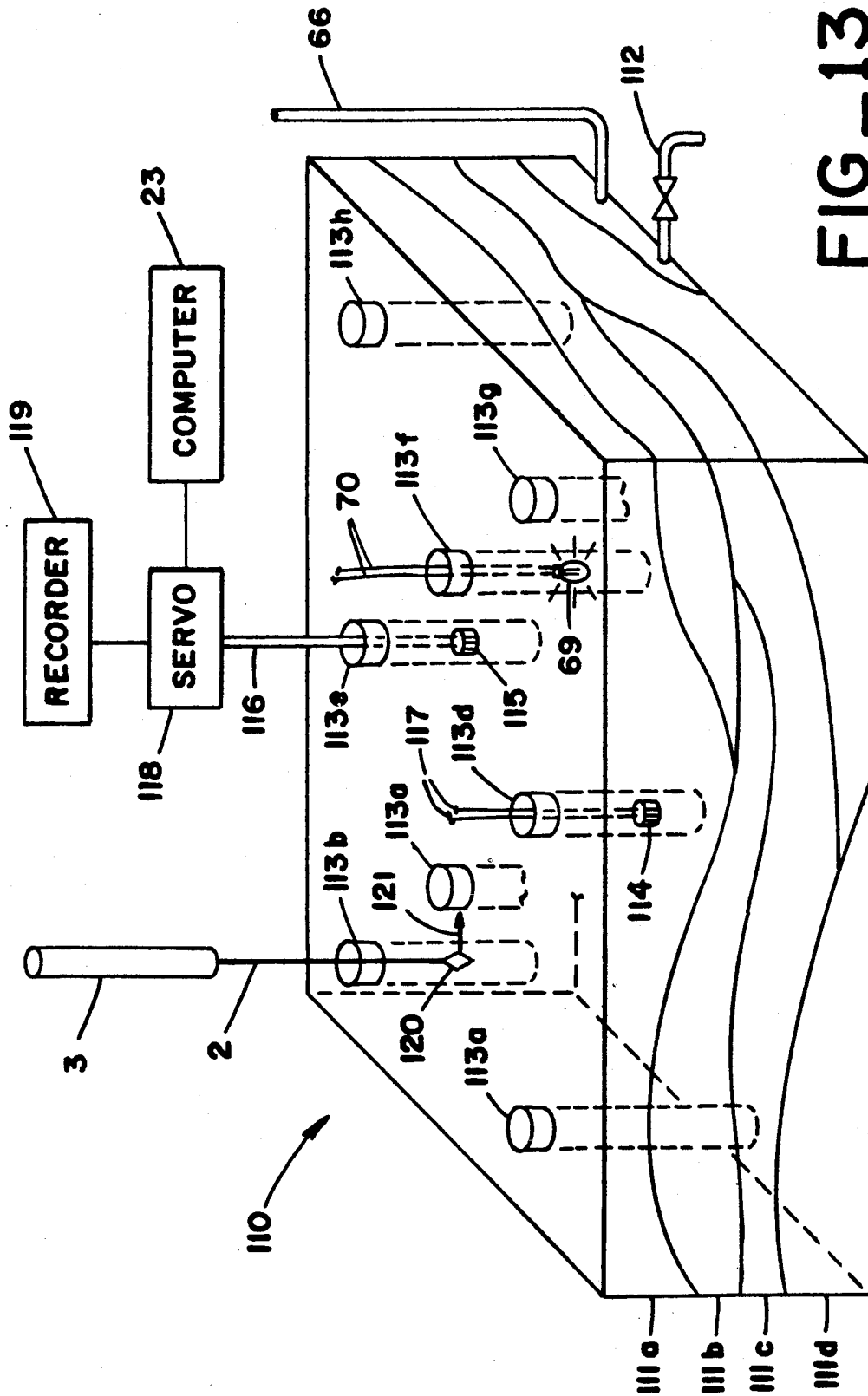


FIG-12



METHOD AND APPARATUS FOR IMAGING POROUS MEDIA AND METHOD FOR FABRICATING NOVEL OPTICAL MATERIALS

FIELD OF INVENTION

The present invention relates to the field of laboratory petrophysics, and more specifically, to using light to measure rock and fluid properties within a given formation.

BACKGROUND OF THE INVENTION

Determining subterranean reservoir properties is an important function for a wide array of applications, such as the production of minerals, e.g., oil and gas, groundwater technology and modeling contaminant transport in the subsurface. These properties include the permeability, wettability, porosity and grain size of the rocks, as well as the large scale flow patterns in the rock formations. The present invention lends itself to all of these areas.

The permeability of a material is a measure of the ability of a porous medium to transmit fluids through its pore spaces. For sufficiently slow, linear, incompressible steady flow it is described by Darcy's law:

$$K = \frac{q\mu L}{\Delta P A}$$

where

K=permeability, darcys (d),

q=flow rate, cc/sec,

μ =fluid viscosity, centipoise (cp),

L=sample length, cm,

ΔP =fluid pressure differential across the sample, atmospheres (atm),

A=sample cross-sectional area perpendicular to flow direction, cm².

The most commonly used permeability units are the "darcy" (d) and "millidarcy" (md). A rock having one darcy permeability conducts 1 cc/sec volume of 1 cp viscosity fluid through a cubic sample having 1 cm length sides under a pressure differential across the sample of 1 atm. Normally, permeability is determined by taking core samples from the reservoir and carrying out well defined measurement techniques, well known to those skilled in the art, on the samples. Several such techniques available for making these measurements are described in PETROLEUM PRODUCTION ENGINEERING - DEVELOPMENT by L. C. Uren, Fourth Edition, McGraw-Hill Book Company, Inc., 1956 and in American Petroleum Institute, API RECOMMENDED PRACTICE FOR CORE-ANALYSIS PROCEDURE, API RP 40, 1960.

More particularly, permeability plays a very important role in describing the fluid flow in oil and gas reservoirs. Two primary methods of measurement are practiced in the industry: steady state method and the dynamic displacement method. In each a cylindrical core is first saturated with water or brine and then oil flooded to irreducible water saturation. The core is then water flooded or brine flooded and the pressure drop across the core is measured along with the oil or water or brine production. The average saturations within the core are determined from the overall material balance. However, the steady state method requires lengthy measurement times since it requires stabilization of the fluid flow; while the dynamic displacement method

does overcome this, it suffers from capillary end effects, and is therefore only effective for high flow rates.

Both of the above described methods of measuring permeability are additionally limited in the information they provide. Specifically, both methods provide only the average or bulk permeability for the core, and can only achieve a resolution on the order of about an inch or so, where core diameters are in the range of 1 inch to 4 inches. Additionally, it is well known that permeability can vary considerably in sandstones over a distance of only one or two millimeters. The degree of variation in permeability has justifiably received much attention in recent years. Information about permeability variation within a formation can provide valuable information about the geological characteristics of the formation. This information is useful in predicting how an oil field will develop, the yields that can be expected, and how it might compare or contrast with already known and developed fields. Running flooding permeability tests, as described above, on very small diameter cores is not an acceptable solution to the problem, since the permeability can still vary considerably along the length of the core. Furthermore, running flooding tests on small diameter, small length cores is not practical because of hydraulic sealing problems and problems introduced by boundary effects.

The only known method that employs light transmission for estimating permeability is by examination of thin sections of the core. Thin sections of geologic samples less than 60 μ m thick are customarily examined with petrographic image analysis techniques to study the micro-features of the sample. From this analysis, geological interpretations of the depositional and post depositional process which formed the sample can be derived. Moreover, physical qualities such as the porosity and permeability of the sample can be estimated. The permeability of the sample, which depends on an interconnected network of individual pores, can be estimated from the porosity of the sample by a linear regression formula or by the empirical Kozeny-Carman equation. Since a thin section has no meaningful permeability itself, the above method gives only an indirect and qualitative estimate of the permeability of the parent volume of rock from which the sample was derived.

A need thus exists for a method to directly measure the permeability and permeability variation in a core having a macroscopic thickness (i.e. a thickness of many layers of grains), with resolution on the order of millimeters. There have been some efforts to obtain permeability measurements in the "less-than-bulk, greater-than-microscopic" range, but most proposed methods are time consuming and cumbersome. For example, Chandler, et al. in their article, "A Mechanical Field Permeameter for Making Rapid, Non-Destructive Permeability Measurements," J. Sedimentary Petrology, 59, 613 (1989), discuss an apparatus (an "air minipermeameter") which achieves a resolution on the order of 2 cms. While this is an improvement over the bulk method, it can still overlook important variations on the millimeter level. Swanson, in his article "A Simple Correlation Between Permeabilities and Mercury Capillary Pressures," J. Petroleum Tech., 33, 2498 (1981), discusses a method for determining the permeability of tiny chips of rocks using mercury injection porosimetry. While this method may provide the desired resolution, it is cumbersome and does not provide for a continuous plot

or "map" of the permeability and its variation across the core.

The problem of wettability, of great interest in petroleum production problems, concerns knowing when two fluids (e.g., oil and water) and present in the rock pore space, which fluid adheres to, or "wets", the pore walls or the surface of the rock grains, while the non-wetting fluid occupies the voids between the grains or the pores. The importance and application of this problem is discussed in "Application of Capillary Pressure Measurements to the Determination of Connate Water Saturation," by N. R. Morrow and by J. C. Melrose in *Interfacial Phenomena in Petroleum Recovery* (N. R. Morrow, ed., Marcel Dekker, N.Y., 1991). At present there exists no non-invasive, non-destructive method by which one can determine whether oil or water wets the surface of the rock grains when both fluids are present.

While the permeability of a rock contains information about the grain size, in petrophysical studies it is of fundamental importance to make measurements of the grain size itself. This parameter can be determined from either microscopic measurements, or by measuring with sieves of known grid sizes upon disaggregating the rock into the constituent grains. Alternately, apparatus are commercially available which can determine the grain size of a rock sample by use of a laser. One such apparatus is sold under the name MICROTRACR® by Leeds & Northrup Co. Operation of this apparatus is described in detail in "Rapid Analysis of Submicron Particles," by P. E. Plantz and H. N. Frock. This apparatus requires a sample of the composite medium to be disaggregated, the particles are then blown in a cloud through a laser beam, with the resulting scattering effect of the laser being correlatable to the particle size. This effect is also discussed in "Measurement of size and concentration of scattering particles by speckle photography" by Genceli, et al., *J. Opt. Soc. Am.*, V70, 10, 1212, wherein the authors admit, "there are moderate restrictions on the number of particles per unit volume."

The permeability of rocks may be affected by the reaction of clays within the rock. Typically, in their natural state within a subterranean formation, clays are compacted around the grains of the rock. Once the natural source fluid is replaced with another fluid, the clays may swell, plugging the channels connecting the pores, and lowering permeability. It is desirable to know not only the total change in permeability, but also the rate at which permeability changes. Current means in the art for determining the effect that different fluids may have on permeability require flooding the core with the various fluids and measuring the bulk permeability. In this manner, however, data can only be collected at various times, rather than in a continuum. Furthermore, it is difficult to determine, with this method, precisely how the permeability may be changing as a function of time.

Previous methods of optically characterizing cores have concentrated on reflected light. Herbin, et al. disclose in U.S. Pat. No. 4,852,182 a method of longitudinally splitting a core and imaging the cross section by reflected normal light. Along a similar vein, Pruett, et al. in U.S. Pat. No. 4,616,134 disclose a method and apparatus for optical surface scanning of longitudinal cores. However, neither of these methods actually measures properties of the core, other than its variation in color.

Recent advances in imaging technology have been applied to the area of geologic samples. For example,

Smith in U.S. Pat. No. 4,797,906 teaches a method to measure porosity in thin sections by use of X-ray reflectance to stimulate naturally occurring fluorescence in the sample. NMR (Nuclear Magnetic Resonance) has been used in U.S. Pat. No. 4,728,892 wherein Vinegar, et al. teach a method for determining, among other petrophysical properties, permeability by indirect calculation from measured porosity. Vinegar et al. state that a high resolution (1 mm) can be obtained with NMR imaging, however, the method is limited to cores 4.2 cm or less in diameter. In U.S. Pat. No. 4,868,751 Dogru, et al. claim a method for determining permeability that combines the classic method of confining the core to a pressure sleeve with the technology of CAT (Computer Aided Tomography) scanning during the flooding. Dogru, et al.'s method purportedly eliminates capillary effects on permeability in the core, but does not indicate that the method gives a high resolution image of the variation in permeability within the core. None of the methods either teach or suggest the use of light transmission through the sample to measure permeability.

The porous media that are the focus of this invention are non-absorptive to light. A good example of an absorptive material is a thin film of black plastic; while the medium is very thin, no light passes because it is absorbed by the medium. In non-absorptive materials, light might be expected to transmit through the medium and emit from the other side, which it does in many cases. However, in some instances some or all of the light which is transmitted into the non-absorptive medium may not be transmitted through the medium due to diffusion of the light inside the medium. A good example of this latter category is a dense pack of irregular quartz crystals not unlike sandstone.

Light transmission through composite media is a subject that has received much attention recently. Current theories and studies of the phenomenon concentrate on the scattering of laser light within the medium in order to study the mechanism of propagation. Typically, the medium is a smoke or vapor or particles suspended in a fluid, gel or solid with particle densities so low that normally occurring light can easily pass through. (e.g., Ishimaru, Kuga, et al., "Scattering and Diffusion of a Beam Wave in Randomly Distributed Scatters," *J. Opt. Soc. Am.* 73, 131-136, 1983). Other studies have considered the phenomenon of light transmission through a porous bed of spherical glass, as for example Gate, "The Determination of Light Absorption in Diffusing Materials by a Photon Diffusion Model", *J. Phys. D.: Appl. Phys.*, 4, 1049-1056, 1971 (Great Britain). In these studies, the porous media have been transparent to visible light, and so the propagation of laser light through them is not surprising. The concept of laser light transmission through media normally opaque to light was considered and discussed in a paper by Anderson, "The Question of Classical Localization—A Theory of White Paint?", *Philosophical Magazine B*, 52, 3, 505-509, 1985. In his paper Anderson theorized a slab of thickness W of material containing random non-absorptive scatters embedded between two non-random propagating media. Stating that if the slab is thick compared with the conventionally defined mean-free-path 1, coherent radiation will be exponentially attenuated, Anderson went on to state that most of the incident radiation will be scattered diffusely and, since it has been postulated that there is no absorption, the radiation must all come out on one side or the other

of the slab W. Thus there is a clear distinction between the transmission of diffuse, incoherent radiation of a "localized" system and an "extended" system, once the system is sufficiently large. Unfortunately, "sufficiently large" also means "sufficiently opaque" and the experimental problem may not be all that simple according to Anderson, therefore optimum scattering requires structures comparable to the wavelength (i.e., particle diameter is approximately equal to wavelength). In addition, although great complexity may be encountered, the work may impinge on a number of highly interesting and practical systems, such as porous media. This therefore indicates that light transmission through a non-absorptive porous medium such as a macroslab of sandstone, as described herein, is not to be expected at all, since in sandstone the wavelength of a laser light is much less than the particle diameter, and the macroslab, due to its thickness, is sufficiently opaque.

Others have additionally theorized about light transmission in rock. In a paper titled, "Reflectance and Albedo Differences Between Wet and Dry Surfaces", Twomey, et al., *Applied Optics*, 25, 3, 431-437, 1986, the authors discuss why light is preferably absorbed by wet rock over dry rock. The theories developed in this paper suggest that forward light scattering into porous media is dependent on the type of fluid present in the voids. However, the focus of the article is absorption by the media rather than transmission by the media, and no speculation is made as to light continuing to propagate through the media, or that the amount of light transmitted into (i.e., absorbed by) the media might be correlated to the overall permeability of the media.

In petroleum production problems and groundwater studies, it is necessary to predict fluid flow characteristics in a stratified earth, where the permeabilities of the various strata are known or given. Such characteristics are usually determined from computer simulations. In conjunction with such simulations, it is useful to have a scale-model laboratory "reservoir" where the predictions of the simulation can be verified. Thus, what is needed in the art is a simple, non-destructive, non-invasive, effective method for determining various properties of a porous medium. Such properties include permeability, grain size, wettability, porosity and clay swelling of a porous medium, as well as the absence or presence of fluid in the porous medium, type of fluid present, and scale modelling of fluid flow patterns in a stratified porous medium. We have recently discovered that laser light will be transmitted through a macroslab of sandstone, on the order of 1 mm to 20 mm thick, preferably 5-10 mm thick. A phenomenon not expected since such a slab is ordinarily opaque to visible light. We have further determined that the amount of light transmitted through the macroslabs is correlated to the permeability of the slab at the point of transmission. Additionally, we have discovered that the laser transmission through a consolidated sandstone allows for determination of average grain size where the sandstone has a high concentration of particles per unit volume; thereby allowing a nondestructive measurement of said grain size. We have still further discovered that the transmission of the laser light through a macroslab containing water and white oil is dependent upon which of the two fluids wets the grain surface, and allows for a method for continuously monitoring the change in permeability with respect to time in a macroslab core section flooded with various fluids. Finally, it has been found that use of the transmission phenomenon allows for prediction of

fluid flow characteristics when used in conjunction with computer simulation, wherein scale model reservoirs are constructed so that light transmission in said models can be observed and measured.

SUMMARY OF THE INVENTION

The claimed invention provides a method and apparatus for imaging properties of porous media by light transmission through the media. The invention takes advantage of a recently discovered phenomenon that laser light will penetrate a macroscopically thick slab of porous material which is normally opaque to random visible light. Further, the amount of light transmitted through the medium is correlated to various properties of the medium and depends on the types of fluid present in the voids of the medium. Thus, by impinging an intense, preferably collimated light on one side of a porous medium and measuring the amount of light transmitted through the medium, one can determine the permeability, the grain size, the porosity, and the wettability of the medium; as well as the presence, quantities and distributions of certain fluids within the medium.

In one embodiment, the invention is used to measure the permeability of porous media as for example sandstones from geologic formations such as petroleum reservoirs. A conversion function relating light transmission to permeability of the rock for a given fluid is first established by control laboratory measurements and curve fitting. This function can be used for all samples from the same formation (i.e., the same rock type). A laser beam is then impinged on a core sample a few millimeters thick. The sample is scanned by the laser, and a sensor opposite the laser records the light transmitted through the core. The recorded data can then be converted to permeability by the conversion function, and be displayed graphically by any of several means known in the art to give a topological "map" of the permeability. In a variation on this embodiment, a core sample containing clays is flooded with various liquids; the effect the liquid has on the permeability due to clay swelling is measured by light transmission through the sample. In this way, the change in permeability as a function of time can be observed. This same time dependence of permeability can be observed where an initially undisturbed, saturated core section is subjected to dynamic flow. The flow will cause fine intergranular particles to migrate into the pore throats, blocking the flow.

In a second embodiment the invention is used to determine the mean grain diameter of porous media, including naturally occurring media such as sandstones. Reference curves are generated either from computer simulation or measurement of light diffusion in samples of known grain size. The experimental results are then compared to the reference curves to determine actual grain size.

In a third embodiment the invention is used to determine the wettability of porous media such as sandstones. A reference curve is first established correlating light transmission to percent oil and water for both water wet and oil wet conditions. A sample saturated with a known oil/water concentration can then be tested and the results compared to the reference curve to determine if the grains are oil wet or water wet or are in a state of mixed wettability. In a variation of this embodiment the heterogeneity of saturation in a partially desaturated slab of sandstone can be mapped.

In a fourth embodiment the invention is used to determine the presence or absence of a fluid in a porous medium. The fluid can either be static or flowing, and the porous medium can be either naturally occurring or artificially fabricated. Further, the presence of one of two fluids having distinct refractive indices can be determined, as well as detecting mixing of miscible and immiscible fluids with distinct refractive indices. The method is similar to that for measuring permeability, but the conversion function is established for light transmission versus type of liquid, rather than permeability.

In a fifth embodiment of the invention, porous media are used to fabricate scale models of petroleum reservoirs. A light source is then used to simulate fluid flow, and light detectors can be used to predict fluid flow patterns within the reservoir. The embodiment can generally be used to predict fluid flows in any porous medium.

The primary advantage of the claimed method over current methods is that the specific petrophysical property of interest can be measured at a high spatial resolution and further, that the measurement of permeability does not necessitate hydraulic flows in the sample requiring high pressure plumbing, seals, etc.

These and other objects, features and advantages of the present invention will become apparent from the following detailed description, wherein reference is made to the Figures in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to facilitate the understanding of this invention, reference will now be made to the appended drawings of the preferred embodiments of the present invention.

FIG. 1 is a plot of data showing the relationship between laser light transmission through a sandstone and permeability of the sandstone.

FIG. 2 is a drawing of an apparatus for measuring the transmission and attenuation of a laser light through a dense porous medium.

FIG. 3 is a drawing of an apparatus for measuring the change in permeability of a core sample.

FIG. 4 is a plot of simulated data predicting the intensity distribution of the emergent beam from dense porous media as a function of the distance from the axis of the impinging laser beam and the grain size of the media.

FIG. 5 is a sketch of the intensity of laser light transmitted through a slab of sandstone as a function of the distance from the axis of the laser beam.

FIG. 6 is a drawing of an apparatus for measuring the grain size of a porous medium with a laser.

FIG. 7 is a sketch showing the dependence of light transmission through a porous medium saturated with two fluids, on the fluid coating the grains of the medium.

FIG. 8 is a drawing of an apparatus for monitoring fluid passing through a porous medium.

FIG. 9 is a plot of experimental data showing the dependence of the attenuation of a laser through dense porous media on the grain size of the media and the index of refraction of the fluid saturating the media.

FIG. 10 is a plot of simulated data predicting the dependence of the attenuation of a laser through dense porous media on the grain size of the media and the index of refraction of the fluid saturating the media.

FIG. 11 is a drawing showing the relationship between light received by a detector in a model reservoir

and the proximity of a moving fluid interface to the detector.

FIG. 12 is a drawing of a scale model of a geological reservoir using porous media and light to simulate fluid flow.

FIG. 13 is another drawing of a scale model of a geological reservoir using porous media and light to simulate fluid flow.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The claimed invention makes use of a recent discovery by the inventors, combining two unrelated disciplines to develop the present invention. In the first discipline, petrophysics, it is known that the size of the grains in a porous medium will affect the permeability, i.e., in comparing two porous media, one with large grains, one with smaller grains, yet having identical porosity (i.e., void volume), the medium with the smaller grains will have a lower permeability. This is attributed to the higher surface area and consequent increased viscous drag on the flowing fluid. In the second discipline, optical physics, it is known that, when the wavelength of the source light is very small compared to the size of the particles of the porous medium, the diffusive attenuation, or lessening, of light through the medium is a function of the particle size.

This attenuation is due to the greater number of surfaces and the consequent increase in scattering events, and thus diffusion. However, as the theory of light propagation is generally applied to porous media made of glass spheres, and the forward propagation phenomenon, known as forward scattering, is usually explained in view of this geometry, it is not obvious to what extent this phenomenon would apply to sandstone; a medium comprising mineral quartz crystals having irregular shapes and sizes generally in the range 10-1000 μm . The grains in sandstone, for example, are transparent, sometimes having a milkiness or a color to them, and, in free form, are better known as common sand. As common sand is not observed to be transparent there is no reason to expect sandstone to be transparent, and in fact, it is not transparent to naturally occurring light and most artificial light. Even after we theorize that the attenuation of light transmission through sandstone should have a correlation to permeability, in that both are dependent on grain size, the known opaqueness of sandstone suggests that the phenomenon would not be observable, and therefore would not be of any practical value.

It is known from common experience that when grains of one transparent medium are surrounded by a fluid with an index of refraction approaching that of the medium, the medium tends to "disappear" due to the lack of refracted light. For example, glass beads in water are less "visible" than glass beads in air; the index of refraction of water being nearer the index of the glass beads than is the index of air. Therefore, one might speculate that since a "wet" medium is more light-conductive than a "dry" medium, that light might propagate better through wet sand than dry, and the phenomenon could be used to advantage. Yet practical knowledge that wet sand is not transparent in naturally occurring and most artificial lights teaches away from pursuing such a theory.

In experiments attempting to find some correlation between permeability of porous media and light transmission through porous media, we discovered that a

sandstone or sand pack, normally opaque, will in fact transmit collimated light when the medium is saturated with a clear fluid having an index of refraction "n" greater than air and most gases (i.e., $n=1.0$), and further, that the amount of light transmitted through the medium is related to the permeability of the medium at that point, i.e., the higher the permeability, the greater the quantity of light that will be transmitted. However, the effect of attenuation of the light signal relative to the permeability decreases as the index of refraction of the saturating fluid approaches that of the medium itself; at that point where the two indices are equal, the medium becomes completely transparent and there is no attenuation of the signal in the medium. The attenuating effect will occur for saturating fluids with refractive indices greater than and less than the medium itself, but at some point if the difference between the two indices becomes too large, the attenuation increases to the point where little or no light is transmitted. Although some light transmission through dry sandstone has been observed and is even predictable in some instances, the present invention anticipates that the medium will be saturated with a liquid when lasers of relatively low power are used. For high power lasers, the invention will work without the presence of the saturating liquid.

The laser is preferably used as the light source because of its highly collimated nature, wherein coherent beam diameters of less than 1 mm are not uncommon, which maximize propagation in the forward direction for a given amount of incident optical power. Use of a laser is not critical; any directed, collimated beam of electromagnetic radiation with sufficient intensity can also achieve the effect. In fact, as will be seen in one embodiment, a less collimated, isotropic light may be desirable in some instances where the matrix material of the porous medium allows a certain amount of light to pass. Use of the collimated light is preferable, however, when the matrix material is naturally occurring, such as sandstones, as opposed to synthetic, such as glass beads. Collimation of an isotropic light source can be achieved by any of several means known in the art, such as lenses for focusing or parabolic reflectors. Where a laser is used, the polarization state of the laser (i.e., either random or linear) is not important for application in this invention. However, the same polarizing state should be used throughout where data from one application is to be correlated to data from a similar application. The wavelength of the light used is not restricted to a specific value, and can vary from the extreme infrared (IR) to the extreme ultra-violet (UV). However, since different wavelengths give different degrees of transmission for different applications, some wavelengths may be preferable over others. The choice will depend on the individual application. The criteria for selection is to choose the wavelength that is the most suitable for a particular application. "Suitable" includes such factors as intensity of light transmitted, dynamic range of transmission values, filtering effect of natural coloration in the porous medium, and possible grain size range of the medium. L. F. Gate has discussed the effect of frequency on diffusive transmission (The Determination of Light Absorption in Diffusing Materials by a Photon Diffusion Model, J. Phys. D: Appl. Phys., 4, 1049, 1054, 1971 [Great Britain]) and provides data indicating that light scattering, and hence transmission, through porous media is a function of the wavelength of the light as well as the natural coloration of the medium. Wavelengths that are at least one order of magnitude smaller than the

mean grain diameter are preferred, and more preferred are wavelengths two to three orders of magnitude smaller than the mean grain diameter. In light of these criteria, the laser should be an ideal instrument for measuring small scale permeability variations in porous media of macroscopic thickness. In the following discussion, the word "laser" will be used to describe the light source, but this should not be understood as precluding the use of other sources of vectored, electromagnetic radiation which qualify under the above discussed selection criteria.

In the first embodiment of the invention, the laser is used to measure permeability of a porous medium. One requirement is that the individual grains of the medium not be opaque to the light being used. This requirement allows the invention to include naturally occurring media such as those found in geologic formations, such as sandstone, and artificial porous media such as sand or glass bead packs. In one example of this embodiment, the porous medium is Boise sandstone. The first step is to determine the correlation between light transmission through the medium and the permeability of the medium for a given fluid. Note that the fluid saturating the medium to facilitate the optical measurement is not necessarily the same as the hydraulic fluid for which the permeability is being determined. One means of determining this correlation is by measuring permeability of several homogeneous cores by classical means (flooding), then measuring the corresponding light transmission through a macroslab of the corresponding core, plotting light transmission versus permeability, and determining, by any of several means known in the art, a function which fits the plotted data. This function can then be used to convert light transmission readings to permeability for additional samples of unknown permeability. Alternately, the function can be plotted to establish a calibration curve; this curve should be valid for any core taken from the same formation (i.e., the same rock type). This assumption is valid as long as the index of refraction and clarity of the formation particles remain fairly constant, and the permeability variation results from grain size variation and not, for instance, a clogging of the pores by clays, or migration of fine particles clogging the pore throats. These latter effects will be discussed below.

Specifically, several small cores (known here as "calibration cores"), approximately 1" diameter by 1" long, from the same formation are obtained. At least six calibration cores should be used, and preferably 10. However, the ideal number is a number of cores which will give statistical significance to the data obtained therefrom. That is, once the data have been curve fitted, a statistical variance can be determined to see how well the curve fits the data. Depending on the accuracy desired for the final readings, if the curve does not satisfactorily fit the data, more data should be obtained to refine the population used to fit the curve, or to determine if a different type of curve should be fitted to the data. If the primary interest is in permeability variation and not absolute permeability measurements, then the curve will not need to fit the data as closely.

The calibration cores should be homogeneous as to permeability, with no variation of permeability across the sample. One means to determine homogeneity is by microscopic examination of a thin section of the calibration core, a method well known in the art. Alternately, since it is now known that laser light attenuation through a macroslab of a porous medium such as sand-

stone is dependent on the same variables as permeability, i.e., grain geometry, a macroslab, or a section between 1 and 20 mm, and preferably between 5 and 10 mm, of the calibration core can be obtained after the permeability is measured by flooding. A laser beam can then be projected through this core section at several points and the transmitted light measured at the other side of the section. If the transmitted light is not seen to vary from location to location across the core, then the calibration core is homogeneous. However, if the transmitted light does vary, then either the data from that core should be rejected, or several light transmission readings should be taken at several different points of the section and averaged to obtain a light transmission number to correspond with the measured bulk permeability of the original calibration core. If any core section exhibits a color variation, then it should preferably be excluded from the calibration data.

A second consideration in selecting the number and type of samples to be used in developing the correlation function is that the samples should include permeabilities near the high and low ends anticipated in the formation. This will prevent potential erroneous results from extrapolation into regions where there is no data to provide support. Ideally the thickness of the sections used to establish the calibration curve should be the same as the sections whose permeability is to be measured. However, this does not preclude the possibility that results from a test section of a thickness different than the calibration section could not be correlated. For example, by scaling up or down proportionally, corrections for thickness might be made. In establishing the correlation between light transmission and permeability for calibration purposes, even in a "homogeneous" sample several light transmission readings should be taken and averaged. The reason for this averaging is that on some scale even "homogeneous" materials become heterogeneous. For example, due to the small diameter of the laser beam, it is possible that the laser may impinge on a surface irregularity detectable on the beam-diameter scale (< 1 mm) which is undetectable on the desired mapping scale (> 1 mm). This would give erroneous results for purposes of calibration.

Note that the assumption is made that the porous media being investigated are nonreactive to the type of fluid present in the pores. It is well known that some porous media, especially clays, will react with different fluids to change permeability. Thus, a core which might have a permeability of 500 millidarcies (md) when flooded with a 5% brine solution will only have a permeability of 75 md when flooded with fresh water. To test for non-reactivity, one core from the formation should be flooded with a variety of fluids in core flooding permeability tests. If the permeability does not change with the fluid beyond that mathematically predicted from the fluid properties alone, such as viscosity, then the porous medium is nonreactive, and the calibration curve will not be reactivity-dependent. The fluids used in the reactivity test should include oil (preferably a white oil so that light absorption is not a factor), brine (a brine similar to the brine found in the formation is desirable), fresh water, and air. If the core is found to be reactive to different types of fluids, then the calibration curve will need be developed using only one type of fluid, and should be restricted to measurements of cores that are saturated with that particular type of fluid.

Once the calibration curve has been established to a statistically satisfactory level, and an accompanying

correlation function has been determined by curve fitting means to the data, permeability of a macroslab can be measured by use of a laser for any core within the same formation. In the example described, five 1" diameter by 1" long cores with different, yet homogeneous, permeabilities were measured for their air permeabilities. Laser light was then transmitted through a 5 mm macroslab of each core and the light transmission measured. The data from these measurements gives the correlation curve of FIG. 1. While there is not a smooth correlation to the data, it should be noted that only five points have been plotted, and with the exception of point "B" of FIG. 1, a fair correlation does exist given the small data set used.

Generally, the core is not limited in maximum diameter, but should probably be no smaller than 1 cm in diameter. The method is preferably carried out in a dark environment to avoid spurious light which may affect the results. The section should preferably be between 1 and 20 mm and more preferably between 2 and 10 mm thick. The section should be mounted with one face facing the laser and the other face facing the light detector. Although in the preferred embodiment the section is mounted with its face at 90° to the direction of the laser beam and parallel to the light detector, these angles are not critical. However, the geometry for the test apparatus should be the same as the geometry of the calibration apparatus. If the geometry is different, however, mathematical corrections could be made utilizing the variation in geometry and the trigonometric relationship therebetween. The preferred embodiment envisions one laser and one detector in general alignment along a line perpendicular to the face of the section when the laser and the detector remain static with respect to each other. In the preferred embodiment, the laser and the detector are static while the core section is moved through the laser beam until the desired area to be scanned has been completely covered. However, it would be possible to use a small bundle of multiple detectors generally aligned with the laser, as distinguished from a single detector, with the multiple detectors coupled to an averaging device. Alternately, in the preferred embodiment, the core section could be static while the laser and detector(s) are dynamic with respect to the section and move across the face of the section to be surveyed. In a variation on the preferred embodiment, a moving laser and a static array of detectors (with respect to the section) spanning the area of the section to be scanned could be used. In still another variation a static laser is used with respect to a moving detector array and section.

With reference to FIG. 2, in one example the workpiece (1), a water saturated core section 5.5 mm thick and 10 cm in diameter, was scanned with a beam (2) from a 10 milliwatt, 632.8 nm wavelength, Helium-Neon laser (3) with random polarization and 0.68 mm beam diameter. The section was placed in a glass dish (4) and immersed in a bath of water (5). Typically the fluid would be either that found naturally in the section (to preserve its natural properties, as discussed above), or a fluid which might be injected into the formation, such as fresh water or brine in a water flooding operation in an oil field. In the example being discussed, the laser was located approximately 50 mm from the first side of the core. This distance is not critical, however, since the laser beam is highly collimated and does not diffuse over long distances in air. If dust or mist were present in the environment in which the test was being

conducted, then the distance from the laser to the section would be more important. In the example the detector (6) was located within 2 mm of the other side of the section. Generally the detector(s) should be located as close as possible to the section since the light emitting from the detector side of the section is diffuse due to diffusion caused within the section. In this example a single static laser was used with a single static detector, while the section was dynamic. The detector area used was 1 cm×1 cm. The section was scanned in an up and down pattern with readings of the light transmission at the detector recorded at 1 mm intervals, starting with one extreme edge of the section. The section was then shifted 1 mm to the opposite edge, and readings recorded as the section was again scanned in an up and down pattern. This process continues until a grid has been formed scanning the complete section in all directions. While grid spacing of 1 mm×1 mm was used in this example, larger grids may be desirable if less resolution is required.

Smaller or larger detectors may need to be used as a compromise between sensitivity and spatial resolution. Additionally, detectors with higher or lower sensitivities may be required depending on the amount of light transmitted through the section and the capabilities of the signal conversion and recording devices used in the experiment. Since the amount of light transmitted is not only dependent on the properties of the section but also on the geometry of the experiment and equipment being employed, both of which are at the discretion of the experimenter, no absolute detector selection criteria can be formulated.

Typically the detector readings are analog voltages. These analog readings can be stored by any of several means known in the art, or can be converted to digital signals by an A/D converter (7) and stored as a recorded value in any digital data collection device, such as a computer (8). In this experiment the data was converted to a digital signal by means of a digital voltmeter and then stored in a Hewlett Packard desktop computer.

The recorded values obtained can then be displayed graphically to give a "map" of the light transmission through the section at any given point. Since light transmission can be correlated to permeability, this "map" will give a representation of the permeability variation of the core across the section. Alternately, if a mathematical curve fitting formula has been determined for the correlation curve, the recorded values can be applied to this formula, and a "map" of the absolute permeability across the section can be plotted. Alternately, the data could be displayed in a tabular form or used for further calculations.

In a variation on the first embodiment, the invention is used to measure the change in permeability of a core section as a function of time. Such a change can occur for instance where clay is present in the core section. As discussed earlier, often these clays will swell when saturated with fluids other than the natural reservoir fluid. An apparatus for making such measurements is shown in FIG. 3. The workpiece core section (1) is placed in a clear, watertight container (11) having fluid inlet (12) and fluid outlet (13). A photodetector (6) as shown in the first embodiment is placed preferably adjacent to the side of the container (11) against which the section rests. The laser beam (2) from the laser (3) is impinged on the side of the section opposite the detector. The laser and the photodetector are preferably approxi-

mately aligned. The photodetector measurements are recorded either on a chart recorder (14) or by a computer or data logger so that the readings can be correlated to a time measurement. Other means of accomplishing this objective of recording coincident time values and detector measurements which are known in the art can be applied. Initially, in recording these time values and detector measurements, the container and section are flooded with a fluid F1 and the light transmission through the section is measured in this base state. At time $t=0$ a second fluid F2 is introduced into the container by way of the inlet (12). The second fluid displaces the first fluid out of the container through the outlet (13). The measurements from the photodetector are recorded starting at time $t=0$ and continuing until a steady state is reached or the experiment is terminated. The recorded values will be correlatable to the permeability, as taught in the discussion above for the first embodiment, and will indicate how permeability changes over time as the clay in the section swells or contracts. Although the apparatus disclosed only measures light transmission at one point on the section, the method herein described can be applied at various points on the section. Additionally, by first mapping the permeability of the section as described in the first embodiment, variations in the base state permeability can be accounted for when monitoring the change over time in permeability at various points on the section after flooding with the second fluid.

The time dependent reduction of permeability can result from mechanisms other than clay swelling. Specifically, the migration of fine intergranular particles under the influence of flowing fluid can cause the particles to collect in the pore throats, reducing fluid flow and thus permeability. Thus the above variation on the first embodiment could be used to measure the reduction of permeability as a function of time due to the migration of fine particles. An apparatus similar to that shown in FIG. 3 can be used with the modification that the fluid inlet (12) and outlet (13) are oriented on the top and bottom of the chamber (11), respectively.

In a second embodiment the invention described can be used to measure grain size and grain size variation of porous media. The configuration to determine grain size is identical to the configuration described above for permeability mapping. However, for this second embodiment, smaller detectors on the order of 2 mm×2 mm should be used. This invention makes use of the phenomenon that the laser beam, while a pinpoint on the incident side of the macroslab when first impinging said macroslab, appears as a luminous disk on the emergent side, with the maximum intensity at the center of the disk. The intensity in this disk will decrease as the distance from the axis along which the laser is projected increases. The distribution of light across the disk will have a typically Gaussian shape. In one example, numerical simulation of the effect was performed by computer. A three dimensional numerical simulation of ray propagation, using a stochastic approach, was used. In the simulation, a hypothetical light ray is traced as it propagates through the medium. As the ray is scattered, its intensity is reduced by the quantity of light reflected, and finally, if the ray emerges at the other side of the medium, its intensity is recorded. This is done for a very large number of rays, on the order of 1 million. In addition, the location at which the ray emerges is recorded.

The results of the simulation are shown in FIG. 4. The results have been visually verified and are consis-

tent with the type of spreading pattern predicted by Genceli, (Measurement of size and concentration of scattering particles by speckle photography, J. Opt. Soc. Am., V70, 10, 1212) albeit for much lower particle densities, yet the same physical phenomenon. In the preferred embodiment correlation curves like that of FIG. 5 are first established either by numerical simulation or by measuring the actual emergent beam profiles of rock samples having known grain size. Once the correlation curves have been established, rock samples of unknown grain size can be tested and their emergent beam profiles recorded. These stored profiles of samples of unknown grain size can then be compared with the profiles of samples of known grain size, and the unknown grain size determined by suitable interpolation means known in the art.

Specifically, an apparatus for determining grain size of a porous composite would resemble that of FIG. 2. The similarity in apparatus is due to the fact that the grain size mapping embodiment is merely a subset of the permeability mapping embodiment. However, for grain size mapping the single detector (5) used for permeability mapping is replaced by a fixed array of detectors covering the entire area of the section to be scanned. Detectors having the smallest possible area are preferred, with minimal but discernible spacing between detectors preferably 0.1 mm or less. This will give high resolution, a desirable feature of this embodiment. Detectors having an area of 2 mm×2 mm are commercially available, as for example from Silicon Detector Corp. of Camarillo, Calif. As discussed in the first embodiment, various combinations of static and dynamic arrangements can be configured between the laser beam, the core section and the detectors. However, in the preferred embodiment the section and detector array are static with respect to a dynamic laser beam. Using automated means known in the art, a complete system can be created for mapping grain size of a core section as a function of the surface spatial coordinates of the section. Further, these measurements can be part of, and simultaneous with, the permeability mapping measurements described in the first embodiment. With reference to FIG. 6, the workpiece (1), a core section, is placed on a static array of detectors (20). The core is preferably saturated with a liquid such as water or white oil, and can be immersed in a bath of the liquid in a glass dish as in the example in the first embodiment. The glass dish and liquid are omitted from FIG. 6 for simplicity. The individual detectors (10a through 10in) of the array (20) are connected by leads [generally (21)] to an analog to digital signal converter (22), which sends the converted digital signal to a digital computer (23). The outputs of the individual detectors can be read individually or addressed more efficiently through a multiplexer known in the art. The digital computer (23) also controls a servo control mechanism (24) which in turn controls servo motors (25) and (26) which position the laser (3) by any of several means known in the art, such as the rack and pinion positioner (27) shown. The computer (23) is programmed to move the laser (3) in predefined increments in the horizontal and vertical directions (corresponding to x and y coordinates) until the entire core section has been scanned by the laser beam (2). At each position the laser (3) is held steady while the (x,y) coordinate position and the corresponding outputs from the detector array (20) is recorded by the computer (23). After the complete core section has been scanned the data recorded by the computer is

processed to generate an output, which may be a graphical display (28). In the preferred embodiment the output is a qualitative topological "map" of the grain size. The amplitudes of the elevations in the map correspond to the full width at the half-power point of the emergent beam as recorded by the detectors, as demonstrated graphically by FIG. 8. Areas with finer grains will have wider distributions, and hence higher "peaks" in the topological map. Alternately, inverses of the emergent beam width could be recorded such that the "peaks" would correspond to larger grain sizes. As discussed in the above paragraph and similarly for permeability mapping in the first embodiment, the light transmission values themselves could be mapped to show relative variation in grain size as a function of location, or, given correlation data developed previously, actual grain sizes can be plotted as a function of location allowing development of a quantitative topological grain size map.

In a third embodiment of the invention, light transmission through a porous medium is used to determine the wettability of the medium. If a porous medium is saturated with a combination of two immiscible fluids, such as white oil and water, one fluid will preferentially coat the grains while the other fluid will fill the pore voids. The fluid coating the grains is known as the "wetting" fluid, and the phenomenon is referred to as "wettability". The affinity of the wetting fluid for the grains is a function of several variables, including the fluid properties and whether one fluid was present before the other. The invention makes use of the discovery that when the wetting fluid has an index of refraction closer to that of the porous medium particles than does the pore filling liquid, light transmission through the medium will approach the maximum. Alternately, when the pore filling fluid has an index of refraction closer to that of the porous medium particles than does the wetting liquid, light transmission through the medium will approach the minimum. This is due to the fact that at optical junctions (the interface between two immiscible substances having different refractive indices), the nearer the two refractive indices are to one another, the more forward scattering there will be. This embodiment can be used to determine wettability characteristics of a porous matrix such as a sandstone under normal reservoir conditions and how this matrix will be affected by changes in conditions, such as treatment with a surfactant.

Specifically, we start with a macroslab of, for example, dry sandstone of known weight having reasonably homogenous permeability. The porosity of the macroslab, which will be referred to as the "section", is first determined by means known in the art. The section is then saturated with a first fluid, for example, white oil, then weighed. A laser beam is then projected against one side of the section and the emergent beam power measured and recorded. The first fluid is then incrementally replaced with a second fluid, which is immiscible with the first fluid and having a refractive index different than the first fluid, for example, water. After each incremental addition of the second fluid the section is weighed and laser light transmission through the section is recorded. The second fluid is added until the weight no longer changes. In the water-replacing-oil case described here, this stage is known as the state of irreducible oil saturation. From the known porosity of the section, the known densities of the two fluids, and the recorded weights, the percent of each fluid in the

section at any given weight can be determined. The data is then recorded and would resemble the upper curve (31) in FIG. 7. The process is then repeated by adding the first fluid to the section initially fully saturated with the second fluid and recording the weights and light transmission values. When this second set of data is plotted it will resemble the lower curve (32) in FIG. 7, in the case of oil-replacing-water. The complete FIG. 7 is now a calibration curve for wettability of this porous medium at normal conditions for the two fluids. Conditions can now be varied, for example, the section can be saturated with oil and then replaced with water which has been treated with a surfactant.

In one example of the embodiment, a slab of Boise sandstone 5 mm thick was first saturated with white oil having a refractive index of $n=1.45$. The refractive index of the sandstone matrix medium is that of quartz, $n=1.55$. The oil in the slab was then replaced with water with refractive index $n=1.33$, following the method described above, the laser power transmitted through the slab was measured and recorded at various states of saturation. Once the slab was fully water saturated (irreducibly oil saturated), the water was then flushed from the slab with the white oil, following the stepwise method described above. FIG. 7 shows the measured points, A, B, C and D, with interpolated upper curve (31) indicating the oil-wet grain condition and interpolated lower curve (32) indicating the water-wet grain condition. As discussed above, such a set of curves could now be used to determine what proportion of oil wet grains would become water wet if flushed with water containing a surfactant. A known volume of the surfactant containing water would be added to an oil saturated slab for which wettability curves such as FIG. 7 has been developed. The percent saturation "s" is known, the transmitted power "t" is measured, and point "x" is determined. This point indicates the portion of grains that have become water wet. If "x" falls closer to the upper curve, the sample is more oil wet than water wet. Consequently, if "x" falls closer to the lower curve, the sample is more water wet. The oil previously covering the grains is now free and recoverable. Information obtained by this method is useful in predicting oil recovery increases by use of surfactants in oil fields.

In the manner that permeability and grain size can be mapped as described above in the first two embodiments, similarly wettability can be mapped. This mapping would be preferably done when one fluid is replacing another, wherein several maps would be generated. In this manner the wetting characteristics of the porous material can be observed. By use of a computer, the change in wettability as a function of time could be calculated, and the change plotted to show a "wettability potential" map. The above method assumes that permeability is homogenous throughout the macroslab. However, if it is not, a permeability map can first be generated for a macroslab by the method of the first embodiment, and then corrections can be made for the wettability curves using that information.

Once the permeability for a core section has been determined by the method described in the first embodiment, and the grain size for the same section has been determined by the method described in the second embodiment, the porosity of the section can be calculated from the Kozeny-Carman relation, and the results can be mapped to produce a topological map of the porosity of the section. Thus the invention provides a complete

system for measuring and mapping the petrophysical properties of porous media such as sandstones.

In a fourth embodiment of the invention, laser transmission through porous media can be used to determine the presence and type of fluid in the media pores. This combination of media and fluid may or may not be transparent to non-laser light. However, the embodiment assumes laser light will be used due to the collimated nature of the laser beam which will result in finer resolution of the medium characteristics. Further, this embodiment assumes that the medium has homogeneous permeability over the section surveyed. Finally, this embodiment further assumes the fluid is transparent to the light being used.

As previously discussed, if a porous section is flooded with a non-absorbent (to light) fluid of increasing refractive indices approaching that of the matrix material, light transmission through the medium is seen to increase. Further, as is well known in the art, as the number of optical junctions increases, the scattering increases, and light transmission decreases. An optical junction being a junction between two materials having different refractive indices. Finally, light transmission decreases as the light absorption of a fluid increases. That is, light transmission through a porous medium is a function of the index of refraction of the fluid, the number of optical junctions in the medium, and the light absorbance of the fluid. It is important to note what light absorbance is being considered, as some fluids may be more transparent to one frequency of light than to another. Due to this dependence of the light transmission on three independent variables, any method for determining fluid properties by use of light transmission through a porous medium containing the fluid will need to hold two of the variables constant. In this embodiment, it is assumed that the light absorbance of the fluid remains constant while either the index of refraction or the number of optical junctions vary. Thus, this embodiment has two variations.

Since homogenous permeability of the medium is required for this embodiment, an artificially fabricated medium is preferably used. However, naturally occurring media can be used, but their homogeneity should be first assured by the method described in the first embodiment. One means for fabricating the porous medium is to create a pack of transparent beads, preferably glass or quartz, and preferably irregularly shaped or having multiple surfaces to maximize the scattering effect. The pack will be referred to hereinafter as a "sand pack". However, as discussed, artificial "sand" can be used as well as naturally occurring sand. The choice of size of the grains to be used should be made so as to optimize the selection criteria; the choice is a compromise between 1) the stronger attenuating effect of smaller grain sizes, suggesting the use of larger grains; and 2) the larger sensitivity to fluid refractive index change for smaller grains, suggesting use of smaller grains. The sand pack can be fused together or simply contained in a chamber for the purpose of maintaining the structural integrity of the pack. The thickness of the sand pack will be a function of the particular application, and light transmission and dynamic range of the transmission should be the primary criteria for choosing the thickness. The attenuating effect of the grains highlights the advantage of the porous medium approach over an approach where the refractive index of the fluid alone is monitored. In the former approach, there is a much higher sensitivity of the transmitted light to

changes in refractive index of the fluid than in the latter approach.

In the first variation, the index of refraction of the fluid filling the pores of the medium varies. One method by which this can occur is if two miscible fluids having different refractive indices are mixed, resulting in a fluid with an index of refraction different than either of the individual fluids. An example of such a mixture is toluene and water. This variation could be used to detect contamination of one fluid miscible with another having a different index of refraction. An apparatus for accomplishing this is shown in FIG. 8. With reference to FIG. 8, in this example a porous medium (41), fabricated from transparent beads (42), is contained in a chamber (43) which is used to conduct the fluid (45) to be monitored or a slipstream thereof. The chamber has at least two opposing points (44a) and (44b) which are transparent. The remainder of the chamber is preferably opaque to minimize light propagation within the walls of the chamber to the detector. The beam of collimated electromagnetic radiation (2) from the radiation source (3) used to monitor the fluid is projected through the transparent portion of the chamber to a light detector (6) adjacent to the chamber. The output (46) from the detector can be used for any number of functions. For example, it can be connected to an analog output indicator (47), converted to a digital signal and further processed, or coupled to an electrical switch to activate an alarm or other device. As the fluid passes through the chamber the amount of laser light which is transmitted to the detector will vary as index of refraction of the fluid varies. One example of an application would be a chemical manufacturing process where contamination is possible, as for example in alcohol manufacturing where water contamination can occur. A slipstream of the production stream could be diverted through a chamber as described above and checked for variation of the index of refraction with the laser as described. If the index of refraction varies beyond a predetermined acceptable level, the output from the detector could be used to signal an alarm or shut down the process.

Another application of the variation of this embodiment would be to use the output signal to calculate the percent of contaminating fluid present. If the amount of light transmitted through the medium when fully saturated with each liquid is known (by measurement), and then the light transmitted in a mixture of the two liquids is measured, mixing laws known in the art can be used to calculate the percent of each liquid present in the mixture. This variation and its applications and examples could find uses in chemical, petrochemical, pharmaceutical, food and other manufacturing processes.

A second method by which the index of refraction of the fluid saturating the medium can vary is if the medium sees different fluids with different refractive indices at different times. For example, in a phase separation process in which two or more fluids with different densities and different refractive indices are allowed to settle out in a vessel and are then pumped out of the vessel, the embodiment could be used to detect the presence of the different fluids in a common pump out line. The output from the detector cell could then be used to switch a directional valve to isolate the different fluids into different storage vessels. In one example of this variation of the embodiment a non-reactive sand pack of uniform permeability was saturated in turn with toluene (index of refraction $n=1.49$), with water ($n=1.33$), and air ($n=1.0$, i.e., the sand pack was dry).

After each saturation, the laser light attenuation through the macroslab was measured, with results shown in FIG. 9. As FIG. 9 indicates, the general shape of the curve plotting attenuation as a function of grain size of the medium remains essentially the same for the three saturating fluids (curves 1, 2 and 3). However the experimental results indicate that the attenuation curve shifts upward to a less attenuated region (i.e., towards less negative values) as the index of refraction "n" of the saturating fluid increases. In a medium with constant grain size, if the attenuation is a known measured value then given a set of curves similar to those of FIG. 9, and assuming constant light absorption of the fluid, the index of refraction of the fluid saturating the medium can be determined. If only a few saturating fluids are possible, each with a distinctive index of refraction, then the saturating fluid can be identified. FIG. 9 also shows that smaller grain size of the medium will result in greater sensitivity, i.e., greater differences in attenuation for two fluids having different refractive indices. In the example discussed, the attenuation rather than light transmission was the recorded value. Attenuation as a recorded value is defined as

$$\text{Attenuation} = 10.0 \log (P_2/P_1) \text{ dB}$$

where P_1 is the power transmitted through a sand pack of one thickness and P_2 is the power transmitted through a sand pack of the same grain size, but a different thickness, where each sand pack is contained between two glass plates. Recording the attenuation in this manner cancels the effects on the transmission of the glass plates, and thus the effect of the medium itself can be isolated. This is desirable if experimental results are to be compared with theoretical results.

The experimental results of FIG. 9 are verified by a three dimensional numerical simulation of ray propagation, as described previously, using a stochastic approach. In the simulation, a hypothetical light ray is traced as it propagates through the medium. As the ray is scattered, its intensity is reduced by the quantity of light reflected, and finally, if the ray emerges to impinge on a detector at the other side of the medium, its intensity is recorded. The results of one simulation are shown in FIG. 10. The simulation generally verifies the experimental results that show that attenuation of light increases (i.e., light transmission decreases) as particle size decreases and as index of refraction of the saturating fluid decreases.

In the second variation of the fourth embodiment the number of interfaces in the medium varies while the other factors affecting light transmission remain constant. This can occur if two immiscible fluids such as air and water or oil and water mix in the porous medium, or if two phases of two single substances are present, such as steam and liquid water. The mixture will create new optical junctions where the two immiscible fluids meet, creating additional scattering in the medium. The increase in the number of junctions will decrease light transmission, and thus the presence of, or the variation in, the quantity of an immiscible fluid can be detected as a result of this decrease in light transmission. An apparatus similar to FIG. 8 can be used for this variation of the embodiment as well. One example of an application for this variation is a petroleum refining process where water is stripped from white oil. If oil becomes entrained in the water, an undesirable effect, the presence could be detected by an apparatus similar to FIG. 8

which would be installed in an outlet line from a condenser unit condensing the stripped water. The output from the detector could then be used to sound an alarm or adjust the process.

In a fifth embodiment of the invention, a fluid saturated porous media on a larger than core scale but still on the scale of a laboratory model can be used to model fluid flow behavior in porous structures. This embodiment is useful for laboratory scale model simulation of complex systems and can be used in conjunction with computer simulation programs to verify results and predictions. The embodiment has the advantage over other flow modeling techniques in that hydraulic flows are not required, significantly simplifying the modeling apparatus. In its broadest form, the system to be modeled is reproduced on a scale version, with regions or zones of differing permeability created from artificial sand or glass bead packs with particle sizes preferably in the 100-1000 μm range. The mean diameter of the grains of the medium should vary no more than does the mean diameter of the reservoir being modeled. One or more light sources is then located within the model to simulate fluid sources, and light detectors are located within the model at points at which fluid flow information is desired. Alternately detectors could be located at transparent model boundaries. The signals received by the detectors will correspond to the fluid flow at the detector locations in an equivalent steady state flow model, in view of the previous discussion of the effect of particle size on permeability and light transmission.

An example of an application of this embodiment is modeling fluid flow in a petroleum reservoir. The model can be constructed to either replicate conditions in a known reservoir using information obtained from cores taken from the reservoir, or the model can simulate a hypothetical reservoir. Because the transmitted light from an isotropic source will be attenuated in the model reservoir within a very short distance (due to the diffusive attenuation as well as the geometric spreading of light), it may be desirable to use glass beads since they permit more light transmission than quartz grains. The reservoir permeability variation is then reproduced as closely as possible by using different layers of different bead sizes. The beads may be mechanically bonded to one another if desired by sintering, clear epoxy, or other means. In an experiment where steady state flow characteristics of the reservoir are the desired parameter to be modeled, the model should be flooded with a liquid that will enhance the light transmission. The fluid should be clear and preferably non-absorbent to light (i.e., "water white"). The index of refraction of the fluid should be selected based on the criteria previously discussed in the first embodiment. The simulation can be enhanced by modeling the movement of a fluid interface within the reservoir. For example, if one fluid is used in actual field applications as a "drive" fluid, either by natural presence (such as ground water or a gas cap) to drive oil toward a production point, this event can be recreated in the model by adding means for injecting a second fluid, having a different refractive index, into the model to "drive" the first fluid with which the model is initially flooded. As a result, some of the light traveling from the light source to the detector will be reflected at the fluid interface, and not arrive at the detector. Upon arrival of the fluid interface at the detector, the amount of light arriving at the detector will change, and the occurrence of the interface arrival can be noted. While this variation may not provide information regarding

flow quantities, it can be useful in predicting dynamic, evolving flow patterns, particularly if several detectors are located throughout the model. Additionally, data collected before the arrival of the fluid interface at the detector can provide valuable information.

As an illustration, FIG. 11 shows an apparatus in Diagram A where a permeable zone generally indicated by (51) with of length D being isolated between two impermeable barriers (52) and (53). A light source (54) is isolated from the permeable zone (51) by a glass tube (55). At the opposite side of the zone from the light source the zone is isolated by a clear wall (56). A light detector (6) is pressed flush against the wall (56) opposite the permeable zone (51). The permeable zone is first saturated with an initial fluid F1 having index of refraction n_1 . A second fluid F2 with index of refraction n_2 is added to the zone by means of a very small transparent injector such as the nozzle (57) which does not interfere with the optical measurement. It is assumed that n_1 is not equal to n_2 , and that F1 and F2 are immiscible. Means to allow fluid F1 to escape as fluid F2 is added is provided, such as the outlet tubes (58) and (59). As the fluid F2 is injected, the interface (I) is created next to the interface (I₁), and moves towards the detector (6). The region ahead of the interface (I) is fully saturated by fluid F1, and the combination of fluid F1 and the matrix material of the porous medium (51) will be referred to as Medium 1. The region behind the interface (I) is filled partly with fluid F2 as it is injected and partly with fluid F1 (i.e., some residual fluid F1 remains behind interface (I) as fluid F2 is injected). This combination of fluids F1 and F2 as well as the matrix material of the porous medium (51) will be referred to as Medium 2. The application consists of recording the power "P" of the light received at detector (6) as a function of time "t", commencing at $t=0$ when the injection of fluid F2 begins. The recorded result would resemble Diagram B of FIG. 11 in the case where $n_1 > n_2$, and n_1 and n_2 are less than the refractive index of the matrix medium. From Diagram B we can develop Diagram C, which gives the location of the interface (I) as a function of time, and thus also gives the velocity of the interface. An example where this information is useful is in the injection of water into a subsurface hydrocarbon bearing reservoir. By knowing the fluid interface velocity and position, well performance can be predicted. Since P is known (by measurement), the distance "d" of Diagram C is determined from Equation A:

$$P = T_o A_d G(d) \Gamma_a \Gamma_I \Gamma_b \left(\exp \left[\frac{-d}{l_2} - \frac{D-d}{l_1} \right] \right)$$

where

T_o =the optical power incident per unit area of the interface (I₁), which can be determined from the properties of the source light (54);

A_d =area of the face of the detector (6);

$G(d)$ =the geometric spread factor for light as a function of $d=r_o/d$ (r_o and d as defined in FIG. 11);

Γ_a =the power reflection coefficient at the interface (I₁);

Γ_I =the power reflection coefficient at the interface (I);

Γ_b =the power reflection coefficient at the interface (I₂);

l_1 =the photon mean free path in Medium 1;

l_2 = the photon mean free path in Medium 2.

Equation A is solved for d by the following method: Since the relationship between P and t is known graphically (FIG. 11B) a value for d is selected, P is calculated from Equation A, and time t from FIG. 11B that corresponds to the calculated P is determined, a plot of d and t is then made. Successive iterations of this process with different values of d , then interpolating a curve between the plotted points, will yield the d versus t curve.

As an illustration of the application of Equation A, with reference to Diagram B of FIG. 11, if fluid F1 is white oil having index of refraction n_1 and fluid F2 is water having index of refraction n_2 , at time $t=0$ the entire zone (D) of Diagram A is oil-saturated, and the detector (6) reads a power level P_1 . In this illustration, it is assumed that $n_1 > n_2$, but this is not a requirement, and the only restriction is that n_1 is not equal to n_2 , and n_1 and n_2 are less than the index of refraction (n) of the matrix material. At $t=0$, $\Gamma_a = \Gamma_b = \Gamma_1$, where Γ_1 is the power reflection coefficient for Medium 1. The value of Γ_1 can be determined from a separate reflectance measurement method known in the art. As soon as the first small volume of water is injected by the injector (57) a very thin layer of Medium 2 forms around the glass tube (55). At that time the power P will suddenly change to P_2 of Diagram B due to the replacement of Γ_1 with Γ_2 , the power reflection coefficient for Medium 2, and the introduction of interface (I), and thus the term Γ_I in Equation A. Following this initial event the power P then drops more gradually as shown in Diagram B as fluid F2 is added and fluid F1 is displaced. When the interface (I) gets very near the interface (I_2) (i.e., $d=D$), the power will be at P_3 of Diagram B. At the point where Medium 2 bridges the gap to the interface (I_2) at the glass wall (56), the power will jump to P_4 of Diagram B. This jump is explained by Γ_b , which prior to the bridging was equal to Γ_1 , now becomes equal to Γ_2 , and the elimination of interface (I), and thus the term Γ_I . Following the bridging event there will be no further change in P , since at that time an optically static system exists. In light of this discussion and diagrams A and B of FIG. 11, the solution to Equation A can now be solved for d since we know that

$$P_1 = K\Gamma_1^2 \left[\exp \left(-\frac{D}{l_1} \right) \right]$$

$$P_2 = K\Gamma_2\Gamma_I\Gamma_1 \left[\exp \left(-\frac{D}{l_1} \right) \right]$$

$$P_3 = K\Gamma_2\Gamma_I\Gamma_1 \left[\exp \left(-\frac{D}{l_2} \right) \right]$$

$$P_4 = K\Gamma_2^2 \left[\exp \left(-\frac{D}{l_2} \right) \right]$$

$$\Gamma_I = \sqrt{\frac{P_2 P_3}{P_1 P_4}}$$

$$\Gamma_2 = \Gamma_I \Gamma_I \left(\frac{P_4}{P_3} \right)$$

-continued

$$l_1 = D \ln \left(\frac{P_1}{K\Gamma_1^2} \right)$$

$$l_2 = D \ln \left(\frac{P_4}{K\Gamma_2^2} \right)$$

where

$K = T_o A_d G(D)$, a constant for a given apparatus.

Additional helpful information can be obtained by measuring the volume of the effluent of fluid F1 from the apparatus as a function of time.

The above example is only one illustration of how fluid flow modeling can be conducted utilizing the present invention. Further refinements of the analysis is possible by one skilled in the art. Starting from this example, more complex models having different geometries can be developed.

In modeling the reservoir, the zones should be contoured to replicate undulations or discontinuities in the reservoir itself. FIG. 12 shows in cross section one example of a model fabricated to simulate fluid flow in a petroleum reservoir. A clear glass vessel (61) approximately 15" in diameter and having straight sides approximately 12" high was used to simulate the reservoir. The bottom of the vessel was internally lined with black epoxy (62) to act as a light seal. A tempered clear glass tube (63) was sealed to the bottom of the vessel with caulk (64). The top portion of the tube protruding above the uppermost layer of sand is coated with black tape or epoxy (65) to act as a light seal. A tubing (66) of 1/4" diameter plastic is run down the inside of the vessel (61) to provide a means for emptying fluid from or adding fluid to the vessel. A first layer of relatively impermeable sand (67) with a mesh size between 140 and 270 was deposited in the vessel. Further layers of differing grain size were deposited to test certain theories in experiment, as explained below. The complete reservoir model was filled with a fluid (68) (water) before the tests were run to improve light transmission. A highly compact, high intensity white light should preferably be used as the light source. In the example being discussed, a Sylvania 750 W tungsten halogen lamp (69), suspended from an electrical supply cord (70), was used as the source light. Because of the heat generated by the intense heat a cooling means such as a fan or blower may need to be employed to keep the light bulb from overheating and prevent possible damage to the reservoir model. Alternately, the light can be activated for only short periods of time if heat is a problem. In the example, short lighting periods were used. Although the results were only visually noted in the experiments, detectors (71) through (81) could have been placed adjacent to the vessel at the different zones and measurements taken. A top zone of relatively impermeable fine sand (82) with a mesh size between 60 and 80 is used as a light seal.

In a first experiment, a layer of relatively permeable glass beads was used to test whether diffusively propagating light would be confined to high permeability channels and not spread out along the vectors (100a-100e), and further, whether it would follow the path shown by the vector (101) and not be impeded by the contour (83) as it would if it merely followed the path shown by vector (102). One side of this layer (84) is left flat and the other side (85) is contoured. The bead

diameters for this layer ranged between 1.0 and 1.05 mm. Results demonstrated that light did follow the path of vector (101). Although the light at the vessel adjacent to section (85) was not as intense as the light adjacent to section (84), this can be explained by the greater path length that light must travel in following vector (102) over vector (101) and the resultant increase in diffusion.

In a second experiment utilizing the apparatus of FIG. 12, the previous experiment was isolated by a region of relatively impermeable glass beads (86a) and (86b) having bead diameters between 0.10 and 0.11 mm. Permeable zones of glass beads (87a), (88a), (88b) and (87b) were deposited along with an impermeable annulus barrier (shown in cross section by (89a) and (89b)). Bead diameters for zones (87a,b) were between 0.45 and 0.50 mm. Bead diameters for zones (88a,b) were between 1.00 and 1.05 mm. Bead diameters for zones (89a,b) were between 0.10 and 0.11 mm. The purpose of the experiment was to test whether light would follow expected fluid flow paths and move along vector (103) into zones (87a) and (87b) and not flow into zones (89a) and (89b). Light propagation along vector (104) is generally anticipated. The visual results show that light will indeed "flow" through the permeable zones in a manner simulating the flow of fluids. Specifically, a bright light was observed at the vessel wall adjacent to zones (88a) and (88b), a less bright light was noted adjacent to zones (87a) and (87b), and virtually no light adjacent to zones (89a) and (89b). The difference in light between zones (87a,b) and (88a,b) can be explained by the somewhat lower permeability of zones (87a) and (87b) compared to zones (88a) and (88b) and also the longer path length the light needs to take in following vector (103) and the resulting loss due to diffusion.

The above results demonstrate the similarity between diffusive propagation of light and fluid flow which forms the basis of the fifth embodiment of the invention. In the dynamic model illustration discussed above where one fluid replaces another, this similarity extends further to include the similarity between the fluid front itself and a "light front" at the interface between the two fluids that moves along with the fluid front.

In fabricating reservoir models, source points simulating either natural reservoir resources or artificial source injection points can be included in the model by placing glass tubes at the desired source locations. That is, more than one source light may be used. In fact, when simulating natural in-situ resources, several source points should be used to simulate a broader distribution of fluid source. When an artificial source such as water or steam injection is to be simulated, the number of actual source points should be replicated in the model. Production points simulating points at which fluid is to be extracted from the reservoir can be simulated in like manner by placing glass tubes at the desired locations within the model and placing detectors inside these tubes. Production points are not necessarily points at which fluid is to be extracted, and may merely be points at which fluid flux is desired to be known. Additionally, a source point can act as a production point, and vice versa. Within a glass tube, a light source or a detector can be moved up or down to simulate injection or production at various depths within the reservoir. The signal from the detectors can be converted (analog to digital) and recorded. The results can be used for such purposes as estimating fluid production at a point, determining flow patterns in a reservoir, determining

optimal location of steam or water injection wells, and determining the optimal depth at which to produce from a reservoir within a given well.

An illustration of a reservoir model incorporating the above features is shown in FIG. 13. The reservoir model, shown generally by (110) is comprised of various layers (11a-11d) of varying permeabilities made up of sand or glass beads. Although not shown for simplicity, the layers would be confined by a vessel enclosing at least the four sides and bottom of the reservoir model. The reservoir model is fitted with a fill line (66) so that liquids may be added to the model and a drain line (112) for extracting liquid or draining the model. The layers (111a-111d) are contoured to simulate the conditions to be modeled. Within the model are several glass tubes (113a-113h) closed at the bottom and open at the top above the uppermost layer (111a). These tubes can either be production points or source points, as discussed above. In the illustration, tube (113f) acts as a source point and has a bright isotropic light (69) suspended from electrical supply lines (70) acting as a source of simulated fluid. Tubes (113d) and (113e) act as monitoring points and have light detectors (114) and (115) inserted in them. Tubes (113a), (113g) and (113h) can be painted flat black to absorb light and simulate production points. The shadowed regions behind these black tubes simulate real-world reservoir conditions where the fluid flow is similarly distributed at production points. The detectors send a signal proportional to the light received at the detector to a meter or recorder (not shown) via leads (116) and (117), respectively. These detectors can be located at different depths within the tube to determine the variation in simulated source fluid as a function of depth within the model. For example, by use of a servo (118) connected to detector (115) by the detector leads (116), the position of the detector (115) can be varied within the tube (113e). The position of the detector (115) and the corresponding light reading could be recorded by a recording means, as for example the strip-chart recorder (119), or could be sent to a computer (23) for further processing. While the isotropic light (69) provides one means of simulating the source, an alternate means would be a laser. In this variation a laser (3) generates a coherent beam of radiation (2) which is projected down the glass tube (113b). A mirror (120) located within the tube is angled so as to reflect the beam in a vectored direction as shown by vector (121). The benefit of using the laser as the simulated source is that much greater transmission distances can be achieved. It should be observed that actual fluid injection points such as described in FIG. 11 can be incorporated into the type of model shown by FIG. 13 to collect data from moving fluid interface modeling.

While the above embodiments of the invention discuss use of an essentially continuous light source, it will be observed by one skilled in the art that the measurements discussed above can be performed in the time domain by using a pulsed light or a pulsed laser and an optical oscilloscope.

From the above description it is evident that the present invention provides a method and apparatus for measuring properties of porous media by use of light or laser transmission through the media. Although only specific embodiments of the present invention have been described in detail, the invention is not limited thereto but is meant to include all embodiments coming within the scope of the appended claims.

What is claimed is:

1. A permeability mapping apparatus comprising:
 - (a) a matrix medium of closely packed particles;
 - (b) a pore filling medium symbiotically interposed within said matrix medium;
 - (c) a means for generating a coherent collimated beam of electromagnetic radiation, said beam of electromagnetic radiation vectored to transpierce a series of locations defining said matrix medium;
 - (d) a means for successively generating an attenuation signal for each of the vectored beams of electromagnetic radiation at each location transpierced by said beam of electromagnetic radiation, and assigning a weighted value based on a correlation function of known permeability to each of the attenuation signals so as to compensate each beam attenuation signal for attenuations at other than one of said matrix locations;
 - (e) a means for reconstructing all said weighted values over said series of locations defining said matrix so as to reconstruct said matrix in terms of each attenuation signal at each of said locations;
 - (f) a means for displaying each reconstructed value to image said matrix medium.
2. The apparatus of claim 1 wherein the matrix medium is embodied in a compartment, said compartment having a means for allowing both ingress and egress of electromagnetic radiation.
3. The apparatus of claim 1 wherein the pore-filling medium has a refractive index greater than the matrix medium.
4. The apparatus of claim 1 wherein the pore-filling medium has a refractive index less than the matrix medium.
5. The apparatus of claim 1 wherein the matrix medium and pore-filling medium are optically transparent.
6. The apparatus of claim 1 wherein the matrix medium and pore-filling medium are optically translucent.
7. The apparatus of claim 1 wherein the means for generating a coherent collimated beam of electromagnetic radiation is a laser source.
8. The apparatus of claim 1 wherein the means for generating a coherent collimated beam of electromagnetic radiation is a parabolic reflector and lens combination used in conjunction with an isotropic light source.
9. The apparatus of claim 7 wherein the wavelength of the electromagnetic radiation is at least one order of magnitude smaller than said matrix medium's mean grain diameter, preferably said wavelength being two to three orders of magnitude smaller than said mean grain diameter.
10. The apparatus of claim 9 wherein the matrix medium is Boise sandstone.
11. The apparatus of claim 9 wherein the matrix medium is between 1 mm and 20 mm thick, preferably between 2 and 10 mm thick.
12. The apparatus of claim 11 wherein the means for successively generating an attenuation signal is a light detector system, said detector system in general alignment with the laser source along a line perpendicular to the laser's collimated beam, said detector system positioned on a side opposite of that which is transpierced

by the laser's collimated beam, and generating attenuation signals proportional to the total attenuation of beams passing through said matrix at a plurality of locations defining said matrix.

13. The apparatus of claim 12 wherein the means for reconstructing all weighted values in response to said beam attenuation signals is a digital computer comprising:

- (a) a means to convert said attenuation signals into digital signals;
- (b) a means to store said digital signals;
- (c) a means responsive to said stored digital signals for converting digital signals into corresponding analog signals proportional to said derived weighted values.

14. The apparatus of claim 13 wherein the means for displaying each reconstructed value is a cathode ray tube means, responsive to said analog signals, for generating a pictorial representation of all matrix locations transpierced by said beam with a proportional intensity.

15. The apparatus of claim 1 wherein permeability changes over time are determined, further comprising: a sealed container having a fluid inlet and fluid outlet, said container housing a matrix section; and a first fluid, and a second fluid to displace the first fluid within the container, said second fluid reacting with clays present in said matrix section to cause a change in permeability.

16. The apparatus of claim 1 wherein grain size and grain size variation of the matrix medium are measured, and where said means for generating an attenuation signal is a light detection system comprising a plurality of small light detectors in a fixed array.

17. The apparatus of claim 16 wherein the light detectors have an area preferably 2 mm×2 mm.

18. A method modeling fluid flow within a matrix medium comprising the steps of:

- constructing a sealed representation of all zones of differing permeability within a matrix medium;
- interposing a light enhancing pore-filling fluid to symbiotically interact with said matrix medium;
- flooded said matrix medium with an isotropic light source;

- measuring the attenuation of said isotropic light at a plurality of locations within said matrix, said attenuation being correlatable to steady state fluid flow.

19. The method of claim 18 wherein dynamic flow patterns are modeled further comprising the steps of: injecting a second fluid into said matrix to drive the initial pore-filling fluid;

- measuring both the change in attenuation of said isotropic light at the interface of said second fluid and said measuring means, and the time of arrival of said second fluid interface at said measuring means;

- generating a prediction of fluid flow based on measured attenuation as a function of the light source and attenuation measuring means properties reflection coefficients at the fluid interface, and the photon means free path in each zone.

* * * * *

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(52) UK CL (Edition K)
G1N NENX N19B2B N19B2Q N30P0 N30R

(56) Documents cited
US 4678997 A

(58) Field of search
UK CL (Edition K) **G1N NCLA NCLE NCLL NENX**
INT CL⁵ **A61B, A61N, G01V**

(54) **Measuring and treatment tool incorporating broadband stripline aeriels and useful in medical technology**

(57) The tool, for determining the nature of fluid in mammal tissue or cancer therapy by hyperthermia transmits, and optionally receives electromagnetic radiation over a broad band of 2KHz – 1GHz and can determine resistivity and dielectric constant. It incorporates at least one transmitting and receiving antenna. Each antenna comprises a coaxial cable 151 connected to stripline adapter 153, which is connected to a stripline (155) having a metallic central strip (159). A strip face 161 is bent at approximately right angles, and has a length that is compatible with the desired frequency coverage. A ground plane 165 extends from the stripline adapter to the right angle bend, and a dielectric 167 fills the space between the centre strip and the ground plane. An enclosure comprising four metallic walls 181 surrounds the stripline, and is in electrical contact with the ground plane and the stripline adapter and a lossless, non-conducting material fills the enclosure. The antennae are positioned so that the strip face lies flush with the tool face, to permit electromagnetic energy to be transmitted into and out of the material to be analyzed. Amplitude and phase of the received signal are monitored.

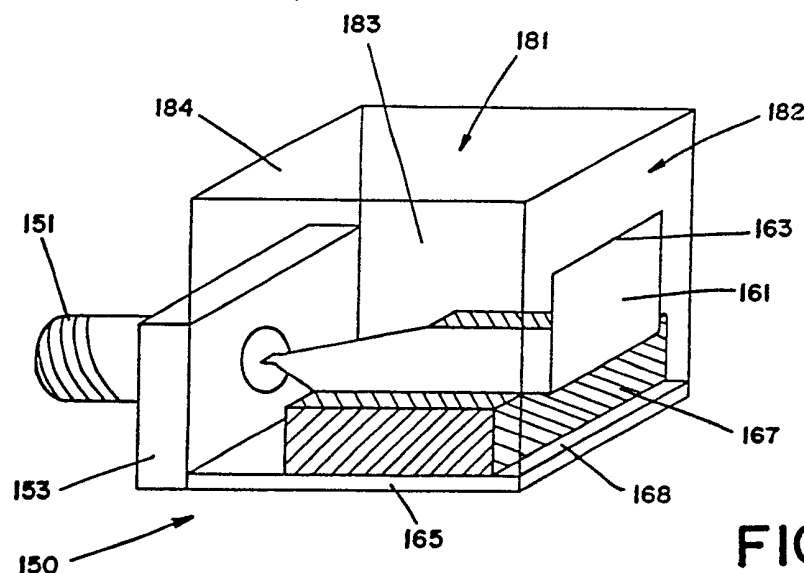
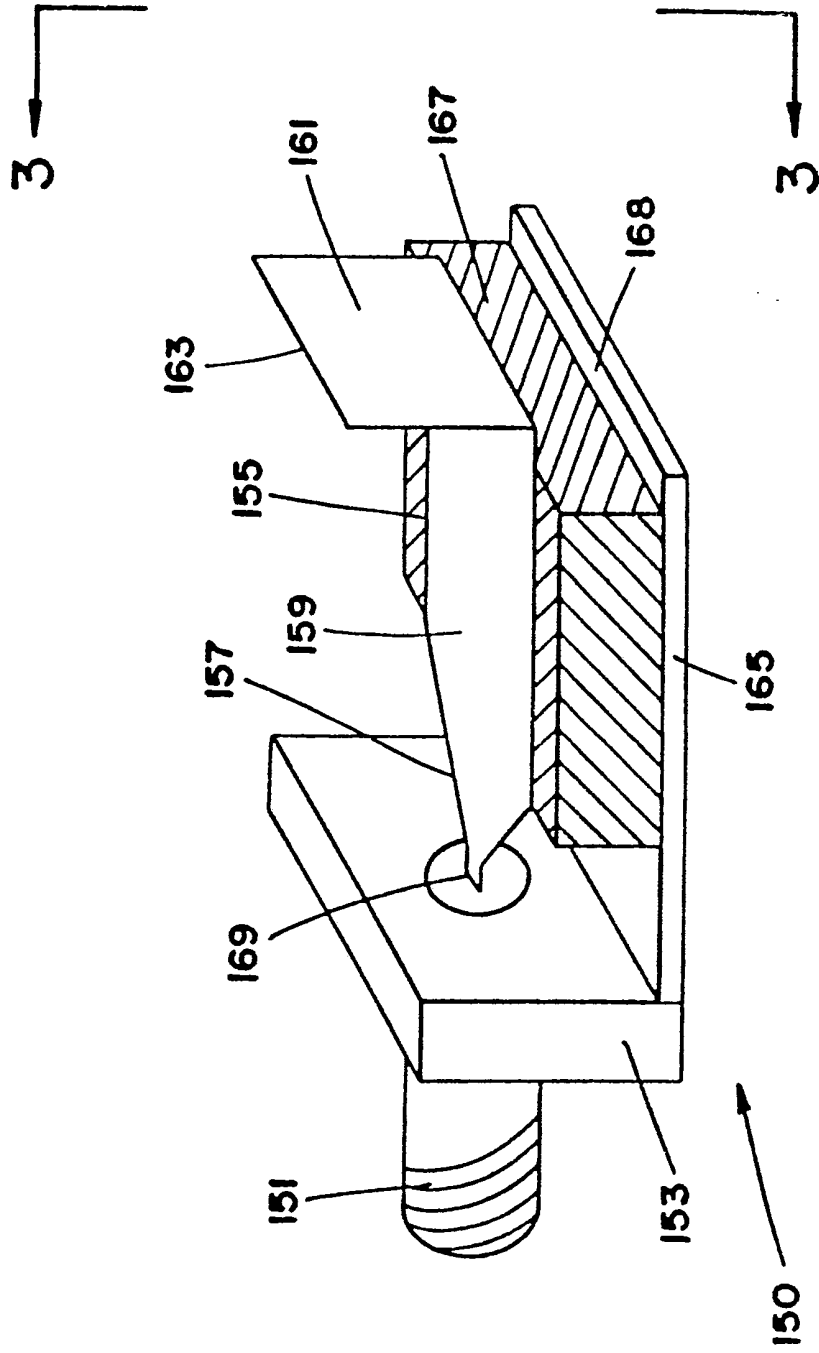


FIG 2A

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

GB 2 251 080 A

FIG_1



FIG_2

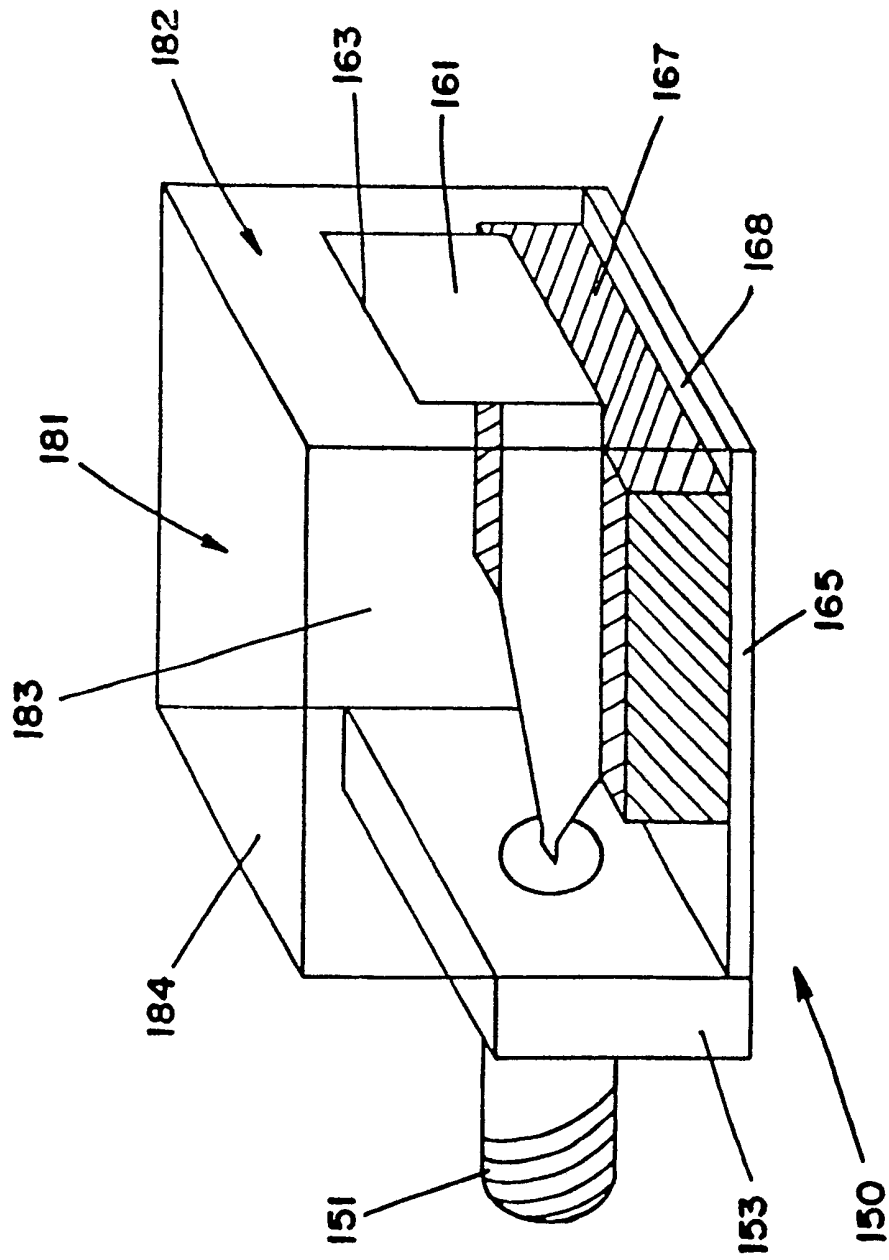


FIG-2A

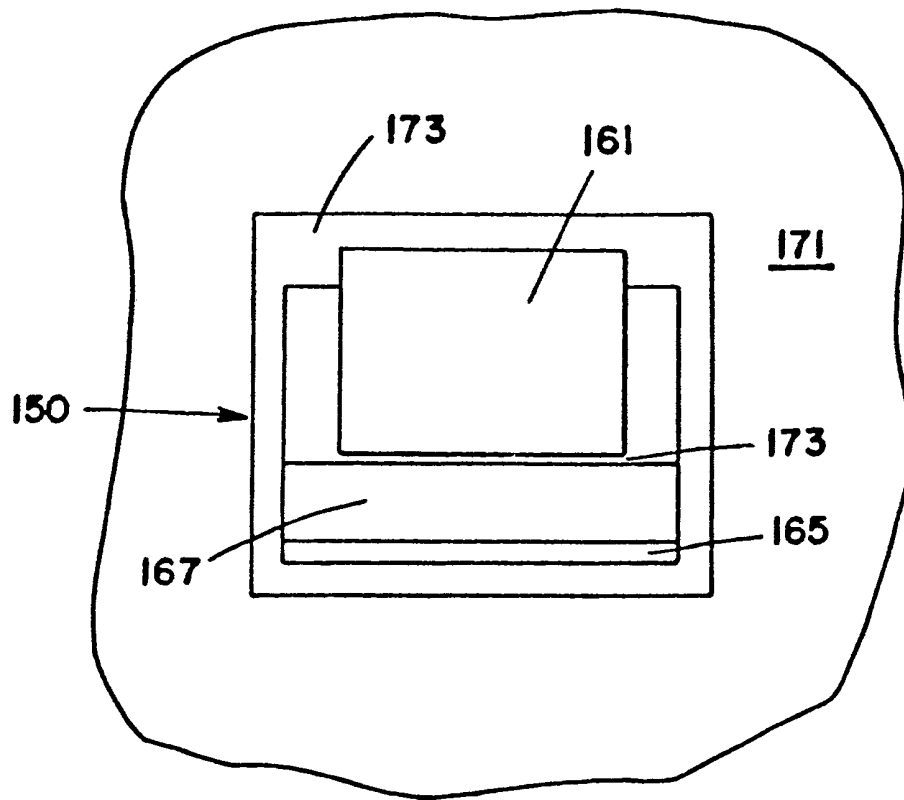
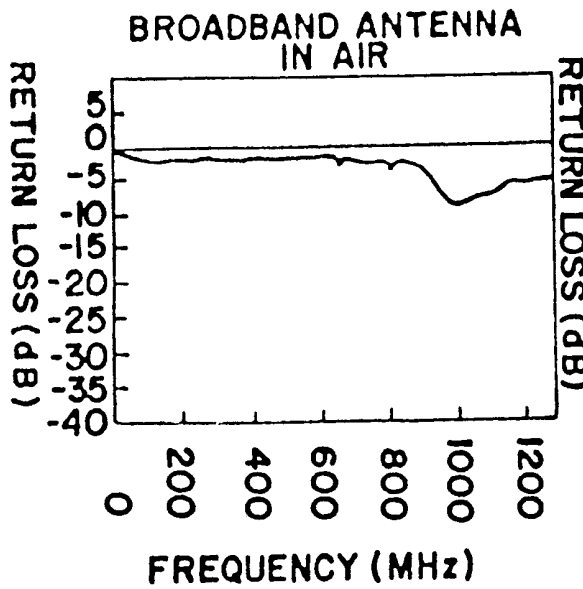
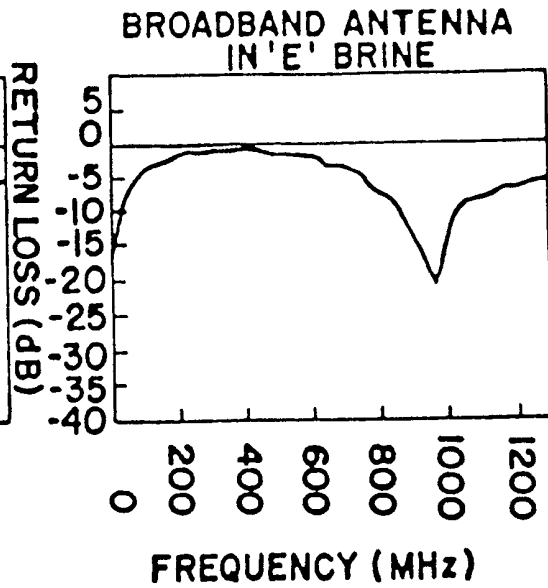


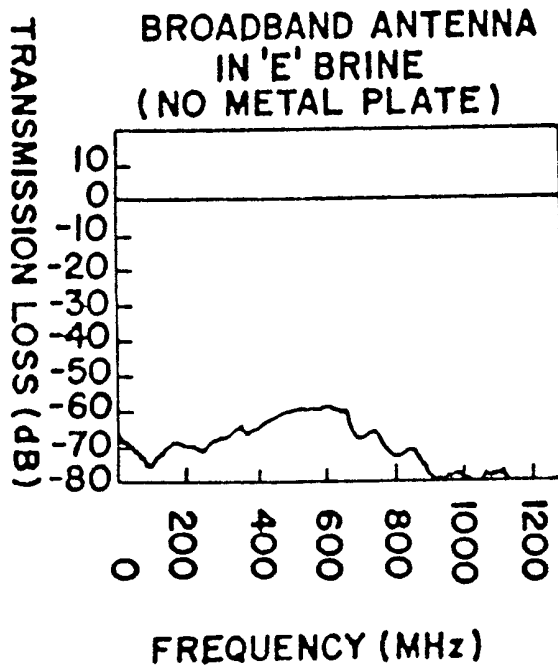
FIG _ 3



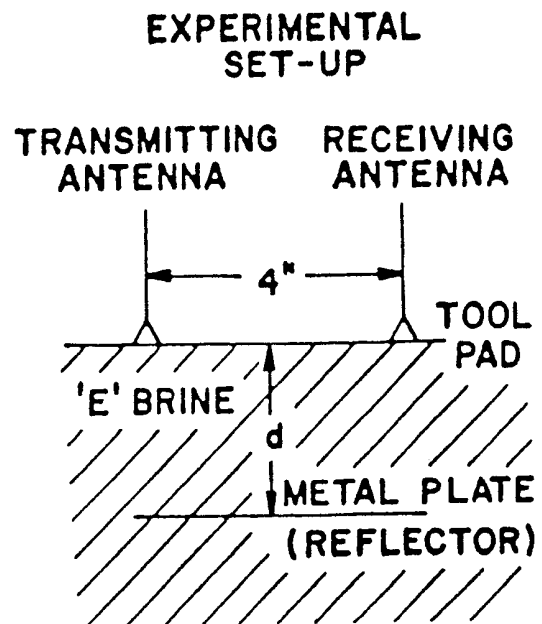
FIG_4A



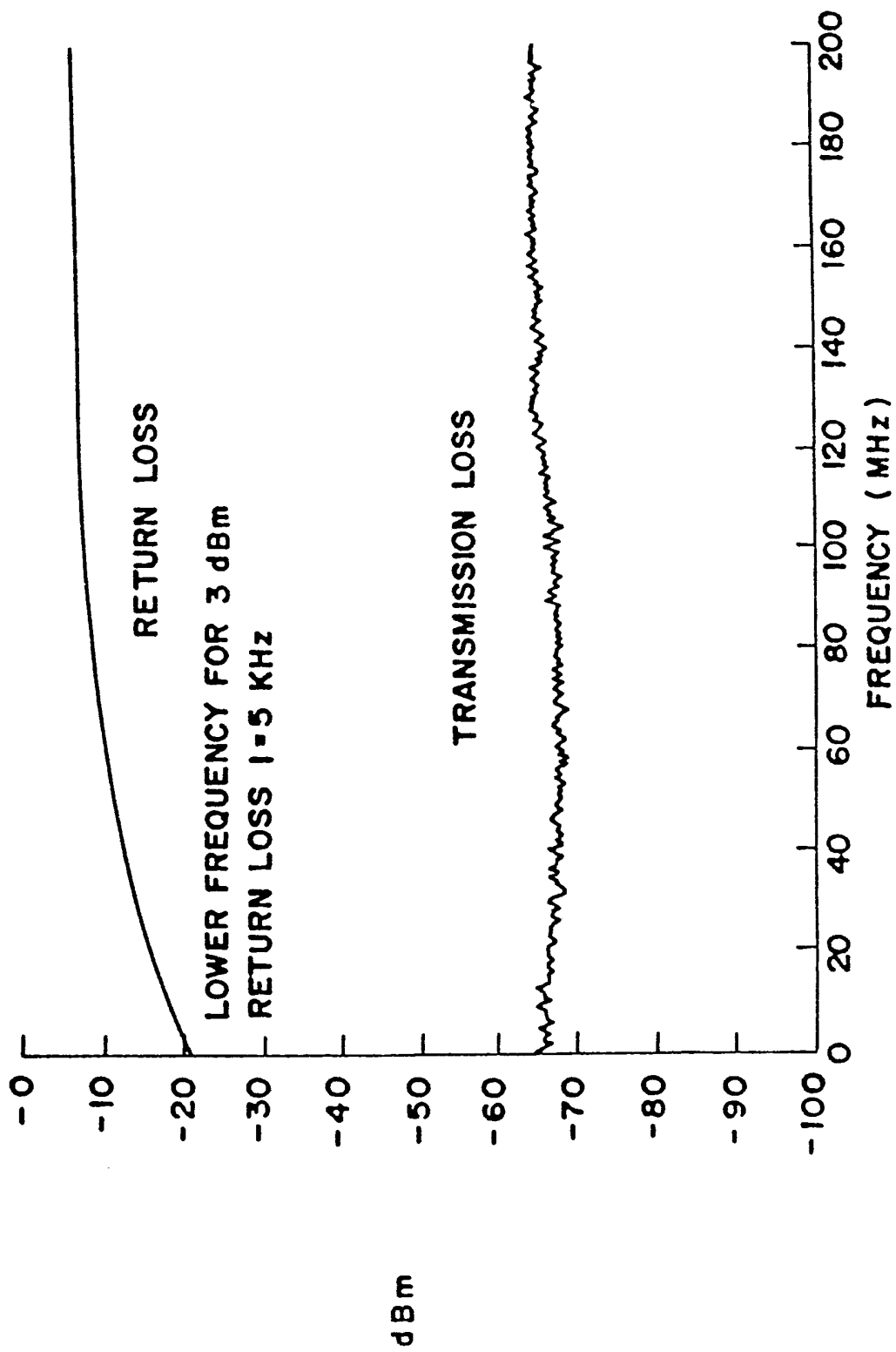
FIG_4B



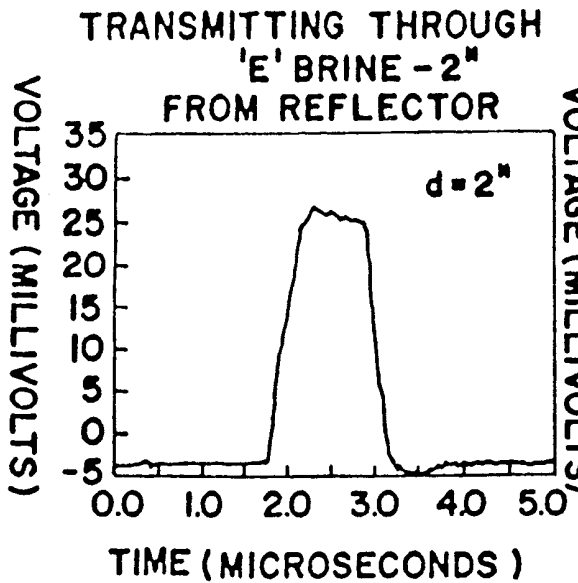
FIG_4C



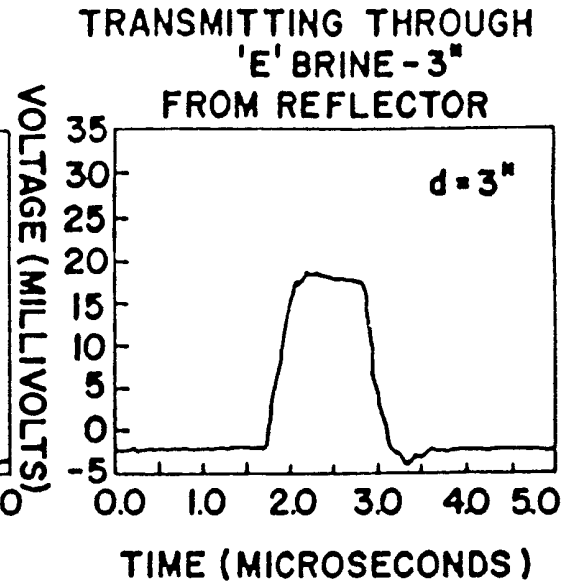
FIG_4D



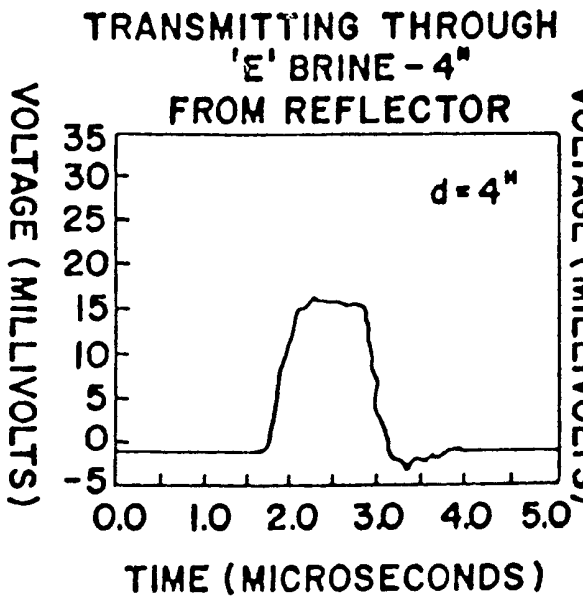
FIG_5



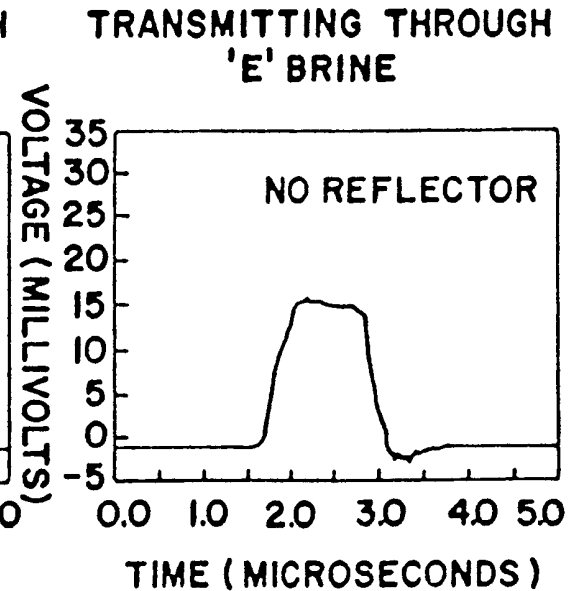
FIG_6A



FIG_6B



FIG_6C



FIG_6D

-1-

01 METHOD AND APPARATUS FOR BROADBAND ELECTROMAGNETIC
02 ENERGY COUPLING

03
04
05
06 The present invention relates generally to the
07 electromagnetic coupling and analysis. More specifically,
08 this invention provides an antenna which can combine the
09 functions of various resistivity and dielectric constant
10 devices into a single tool, capable of operating over a wide
11 range of frequencies. It is particularly useful in the
12 field of medical technology.

13
14
15
16 In the field of medical technology, it is well known that
17 electromagnetic energy is useful in various types of
18 diagnoses and treatments. For example, recent statistics
19 show that pulmonary and cardiopulmonary diseases are
20 responsible for more than three million hospital admissions
21 and 30,000 deaths every year in the United States.
22 Pulmonary abnormalities are virtually always associated with
23 changes in lung water content or distribution. Most workers
24 agree that there is no single, nondestructive method
25 available to detect accurately early changes in lung
26 water content.

27
28 For a clinically useful technique, it is desirable to detect
29 early changes in both the extravascular lung water, which
30 strongly reflects most pulmonary abnormalities, and the
31 intravascular compartment. Recently, the use of the
32 electromagnetic methods to detect changes in lung water
33 content have shown promising initial results, particularly
34 for detecting small variations in water content.

01 Particularly at microwave frequencies, changes in the
02 dielectric properties of tissue are closely related to the
03 amount of water present. Electromagnetic techniques,
04 therefore, basically utilize changes in the permittivity and
05 conductivity of the lung region to detect changes in lung
06 water content. This method has the advantage of using
07 highly penetrating electromagnetic signals rather than
08 ultrasonic signals which are both highly attenuated and
09 dispersed in the lung. Furthermore, electromagnetic
10 techniques have the potential for continuous monitoring of
11 patients in intensive care units, such as those with heart
12 failure or extensive burns.

13

14 U.S. Patent No. 4,240,445 issued to Iskander et al. and is
15 incorporated herein by reference for all purposes. Iskander
16 teaches a method of coupling electromagnetic energy into a
17 material such as tissue, to measure water content.

18 Measuring lung water content is an especially useful
19 application. However, Iskander's device is so large that
20 only a few antennas can be place on the chest, and the
21 antenna cannot be described as a point source. Also, the
22 electric field vanishes at some distance from the antenna,
23 as the electric fields in the two parallel slots are
24 oppositely directed. Furthermore, a resistor is included in
25 the antenna, which dissipates much of the electromagnetic
26 energy in the antenna itself and introduces a limitation in
27 the power handling capability of the antenna. Additional
28 prior work includes: M. F. Iskander and C. H. Durney
29 (1980): "Electromagnetic Techniques for Medical Diagnosis:
30 A Review", Proceedings of IEEE, vol. 68, no. 1. and
31 M. F. Iskander et al (1982): "Two-dimensional Technique to
32 Calculate the EM Power Deposition Pattern in the Human
33 Body", Journal of Microwave Power, vol. 17, no. 3. There is
34 thus a need for a device that is compact enough to permit

01 placing of many antennas forming an array on a chest to
02 obtain a well-defined image of the chest cavity, a device
03 that has an antenna that can be mathematically described as
04 a point source, and one which does not suffer from
05 cancellation of the electric field at a certain distance.

06
07 A dielectric transmitting and measuring device can also be
08 used to heat an interior portion of a mammalian body to
09 destroy or reduce the size of tumors. Tumor reduction
10 therapy, or cancer therapy by hyperthermia, combined with
11 radiation or drugs is known in the art to either stop or
12 slow down the growth of cancer cells, or cause the death of
13 the cancer cells. (See, for example, Streffer, C., "Cancer
14 Therapy by Hyperthermia and Radiation", Urban and
15 Schwarzenberg, Munich, F.R.G., 1980 and Dethylefsen, L.A.
16 (Editor), "The Third International Symposium: Cancer
17 Therapy by Hyperthermia, Drugs and Radiation, Colorado State
18 University, Ft. Collins, U.S.A., 1980.)

19
20 One such device is disclosed by J. Scheiblich et al.
21 "Radiofrequency-Induced Hyperthermia in the Prostate",
22 Journal of Microwave Power, vol. 17, no. 3, 1982, Ottawa,
23 Canada. Scheiblich et al's device works only at a
24 single frequency.

25
26 A propagating electromagnetic wave has two fundamental
27 characteristics, amplitude and phase. By comparing the
28 amplitude and phase of an electromagnetic wave as it passes
29 receivers, propagation characteristics of the probed medium
30 may be studied. Measurement of these two characteristics
31 may be used to determine the dielectric constant and
32 the conductivity of the media through which the wave
33 is propagated.

34

01 However, no one tool in the prior art is capable of probing
02 or coupling energy into a material over a broad band of
03 frequencies. It is therefore advantageous to extend the
04 frequency range.

05

06 The largest hurdle to developing such a broadband dielectric
07 tool has been the lack of a suitable broadband antenna that
08 can couple electromagnetic energy to and from a material,
09 and that is compact enough to fit within the confines of
10 a tool.

11

12 The prior work is limited in the attempts at electromagnetic
13 coupling, analysis, and treatment, in that no suitable
14 single antenna element has been designed which can couple
15 electromagnetic energy into a material, such as mammal
16 tissue, over a broad range of frequencies, that is also
17 sufficiently compact and is capable of handling high power
18 levels. There is therefore a need for a device and a method
19 for use in such broadband applications.

20

21

22

23 The present invention is surprisingly successful in
24 providing a method and apparatus for combining the functions
25 of various conductivity and dielectric constant devices and
26 electromagnetic energy coupling devices into a single
27 device, capable of operating over a wide range of
28 frequencies. It is especially useful in medical
29 technology applications.

30

31 A measuring or electromagnetic coupling tool, having a tool
32 face, also has a novel transmitting antenna and a novel
33 receiving antenna. Electromagnetic energy is transmitted to
34 a transmitting antenna. A stripline adapter permits the

01 energy to flow to a stripline having a metallic central
02 strip. A strip face of the central strip is bent at
03 approximately right angles, and has a height that is
04 compatible with desired frequency coverage.

05
06 A ground plane extends from the stripline adapter to the
07 right angle bend, so that a distal end of the central strip
08 extends away from it, and a void is created between the
09 center strip and the ground plane.

10
11 A dielectric is positioned to nearly fill the void. The
12 dielectric is comprised of a material having a very high
13 dielectric constant and a very low energy loss. The
14 transmitting antenna is positioned so that the ground plane
15 is fixedly connected to the measuring tool, and the strip
16 face lies flush with the tool face, so that electromagnetic
17 energy can be transmitted into the material to be analyzed.

18
19 An enclosure surrounding the stripline is comprised of four
20 metallic walls which are positioned in electrical contact
21 with the ground plane and the stripline adapter, so that the
22 strip face is nearly centered in the opening created by the
23 walls and the ground plane.

24
25 A loss-less, non-conducting material fills in any remaining
26 open space in the enclosure, so that the non-conducting
27 material forms an additional wall that is really flat with
28 the strip face.

29
30 A receiving antenna is comprised in essentially the same
31 manner as the transmitting antenna, and is positioned in the
32 tool so that it can receive the electromagnetic energy which
33 has traveled through the material being probed. A means for
34

01 monitoring the received energy detects the phase and
02 the amplitude.

03

04 In another embodiment of this invention, broadband
05 measurements are taken to determine the quantity of a fluid
06 in a material, such as water in a lung.

07

08 It is one object of this invention that electromagnetic
09 energy is transmitted and received over a wide frequency
10 range, specifically from a few KHz to a few GHz. A commonly
11 used frequency range is from 2 KHz to 4 GHz.

12

13 The tool may further comprise a pad, which substantially
14 conforms to the surface of the mammal tissue, and holds the
15 antennas. At least one transmitting antenna is necessary.
16 No receiving antenna is necessary, although a plurality of
17 each is often desirable.

18

19 The above and other embodiments, objects, advantages, and
20 features of the invention will become more readily
21 apparent from the following detailed description of the
22 invention, which is provided in connection with the
23 accompanying drawings.

24

25

26

27 Figure 1 is a schematic, sectional view of the inventive
28 device positioned adjacent to mammal tissue.

29

30 Figure 2 shows a top, front, and side view of the novel
31 transmitting antenna.

32

33 Figure 2A is the same view as Figure 2, further illustrating
34 the enclosing metallic walls.

01 Figure 3 shows an antenna mounted on a tool face.

02

03 Figure 4 shows three graphs of transmission and return loss
04 as a function of frequency.

05

06 Figure 5 is a graph of transmission and return loss as a
07 function of frequency, for low frequencies.

08

09 Figure 6 shows four graphs of time-domain transmission
10 measurements at various distances from a metal reflector
11 plate in a brine.

12

13

14

15 In accordance with the present invention, a new improved
16 method and apparatus for coupling electromagnetic energy
17 into a material for determining the nature of various
18 materials and the fluids contained therein and to induce
19 hyperthermia, using a broadband measuring apparatus, has
20 been developed.

21

22 Referring to the drawings, a first embodiment of the
23 inventive broadband tool 101 is shown in Figure 1,
24 positioned around a portion of a mammal body such as a chest
25 cavity 103. A means such as a belt mount 109 positions tool
26 face 111 near the mammal skin 104, such that transmitting
27 antennas such as T1 and T2 and receiving antennas such as R1
28 and R2 are positioned touching the skin surface of 104. The
29 tool face 111 is defined as the surface of the belt
30 mount 109 containing the aperture plane of the antennas, and
31 is preferably a continuous metallic surface. The belt
32 mount 109 may be made of any suitable flexible material that
33 can be strapped around the portion of interest of the mammal

34

01 body. A conducting compound such as a conducting grease may
02 be applied at the interface 113 between the tool face 111
03 and the skin surface 104 to improve coupling between the
04 antennas and the chest cavity 103.

05
06 The region of the mammal body to be investigated may not be
07 electrically homogeneous. In the chest cavity 103 for
08 example, there are organs such as the heart 105, the lung
09 region 106, the vertebra 107, and there may also be a
10 tumor 108. It is often desirable to analyze or treat
11 selected portions of such a cavity 103.

12
13 An analysis of the chest cavity 103, for example, can be
14 done by a dielectric imaging of the cavity. This is done by
15 transmitting electromagnetic energy at a suitable frequency
16 across the chest cavity 103 from a transmitting antenna such
17 as T1, and receiving this energy at a receiving antenna such
18 as Rn. In this way the phase and the amplitude of the
19 propagated electromagnetic wave for the path T1Rn (shown in
20 dashed line) is determined. Since there can be a
21 multiplicity of transmitting antennas Tn and a multiplicity
22 of receiving antennas Rn, a multiplicity of such paths
23 crisscrossing the entire chest cavity can be studied. From
24 this information, using well known techniques, a dielectric
25 image of the chest cavity can be generated. Such an image
26 displays the various organs in the cavity, and when suitably
27 made, can reveal the presence of tumor 108. The dielectric
28 properties, and thus a dielectric image, can be determined
29 as a function of position within the material being probed.
30 Since dielectric image is very sensitive to the presence of
31 water, it can also give an assessment of the lung water
32 content; Cf. "Microwave Methods of Measuring Changes in Lung
33 Water", by M. F. Iskander and C. H. Durney, Journal of
34 Microwave Power, vol. 18(3), 1983, p. 265.

01 Note that although the antennas have been labeled as either
02 transmitting or receiving antennas, any given antenna can
03 serve either function.

04

05 The broadband capability of the antennas is an advantage in
06 the above applications for the following reasons:
07 structures (e.g., heart, tumor) of different sizes require
08 different frequencies for their best definition in the
09 image; highly lossy regions such as fluids may require
10 employment of relatively low frequencies so that the
11 electromagnetic losses are acceptable; in time-domain
12 application, simultaneous information at a multiplicity
13 of frequencies can be developed.

14

15 In the treatment mode, it is desirable to reduce or
16 eliminate the tumor 108 by hyperthermia, i.e., by
17 selectively heating only the tumor region 108 to a high
18 temperature. Thus, by selecting a suitable group of
19 antennas to transmit, one can selectively deposit
20 electromagnetic energy in the region of the tumor 108; Cf.
21 "Two-dimensional Technique to Calculate the EM Power
22 Deposition Pattern in the Human Body", by M. F. Iskander,
23 P. F. Turner, J. B. DuBow and J. Kao, Journal of Microwave
24 Power, vol. 17(3), 1982, p. 175.

25

26 The broadband capability of the antennas is an advantage in
27 the above application because for a given situation, one can
28 select the frequency that simultaneously produces the
29 optimum deposition of power and localization of the heating
30 using known techniques.

31

32 An example of the inventive transmitting antenna 150 is
33 shown in Figure 2. A coaxial connecting means, such as

34

01 coaxial connector 151 is electrically connected to a
02 stripline adapter 153 which is capable of transmitting
03 electromagnetic energy from the coaxial connector 151 to a
04 stripline section with metallic central strip 155. An
05 especially useful stripline adapter is a model No.
06 3070-1404-10 designed by Omni-Spectra, or other types of
07 microwave stripline adapters. Other types of transmission
08 means may be utilized to transmit electromagnetic energy to
09 the antenna. For example, a strip transmission line may be
10 electrically connected to the stripline section having the
11 metallic central strip 155. As a commercial
12 coaxial-to-stripline transition means has been utilized, the
13 dimensions included herein reflect this means. One
14 knowledgeable in the art would realize that the
15 dimensions may be altered to change frequency coverage
16 and to fine-tune performance.

17
18 Metallic center strip 155 has a front end 157, a flat strip
19 body 159, a flat strip face 161, and a distal end 163. The
20 front end 157 is electrically connected to the center
21 conductor 169 of the stripline adapter 153. Solder is a
22 particularly useful connecting means. Flat strip body 159
23 may also be tapered to come to a point at front end 157 to
24 provide a smooth electrical transition between the center
25 conductor 169 and the center strip 155. The strip face 161
26 is bent at approximately right angles to strip body 159, and
27 has a height that is measured from the right angle bend to
28 distal end 163. The height is compatible with the desired
29 frequency coverage. The longer the height, the more lower
30 frequency coverage is allowed. A $\frac{1}{4}$ " height permits a
31 frequency range of approximately 2 KHz $\rightarrow$ 1 GHz. A 5mm
32 height extends the upper frequency limit to approximately
33 2 GHz. An upward frequency limit of 4 GHz is attainable as
34

01 well. The metallic center strip 155 can be made of any
02 metal. Copper, brass, or aluminum are especially useful.

03

04 A ground plane 165 extends from stripline adapter 153 to the
05 right angle bend in the center strip 155, so that the distal
06 end 163 extends away from the ground plane 165 and so that a
07 void exists between the center strip 155 and the ground
08 plane 165. Ground plane 165 is comprised of a metal.
09 Commercial grade stainless steel is particularly useful. It
10 is desirable to keep the ground plane and center strip as
11 short at possible, to permit the apparatus to remain as
12 compact as possible and to allow the use of as many antennas
13 as possible.

14

15 The void between the ground plane 165 and the center
16 strip 155 is largely filled with a dielectric 167. The
17 dielectric 167 should have a very high dielectric constant
18 and a very low loss. By loss, we mean the dissipation of
19 energy. The dielectric 167 can be a ceramic dielectric, and
20 comprised of material such as Barium Titanate or Lead
21 Zirconate Titanate. A crystalline dielectric may also be
22 used, although more expensive. The thickness of the
23 dielectric 167 is determined by the stripline adapter 153
24 used. The dielectric 167 acts to make the capacitance of
25 the center strip 155 very large.

26

27 The construction of the antenna is completed by enclosing
28 the center strip 155 by metallic walls 181, 182, 183, and
29 184, which contact the ground plane 165 and the adapter 153
30 electrically, as shown in Figure 2A. The walls add rigidity
31 and prevent leakage of the electromagnetic radiation. The
32 strip face 161 is approximately centered in the rectangular
33 opening created by the edges of the walls and the edge of
34 the ground plane 165. Thus, the distance between an edge of

01 the strip face 161 and the adjacent edge of a wall is
02 substantially the thickness of the dielectric 167. The
03 entire void space in the antenna enclosed by the walls,
04 including the set back 168 at the dielectric edge, is filled
05 with a loss-less, non-conducting material such as a mixture
06 of epoxy and alumina which sets hard, seals the antenna, and
07 makes it more rugged.

08
09 The ground plane 165 and the walls 181, 182, 183, and 184
10 are fixedly connected to an electromagnetic coupling or
11 analyzing tool as seen in Figure 3. The strip face 161 is
12 positioned to lie flush with the tool face 171 (which is the
13 same as the tool face 111 of Figure 1), so that the
14 transmitting antenna 150 can transmit electromagnetic energy
15 into a material such as mammal tissue. A conductive
16 substance, known in the art, is usually placed on the
17 outside of the mammal tissue, to permit a sufficient flow of
18 electromagnetic energy into the tissue. Void space 173 is
19 filled with a loss-less, non-conducting material such as an
20 epoxy-aluminum compound. The ground plane 165 and the walls
21 181, 182, and 183 connect to the tool face.

22
23 A receiving electromagnetic antenna is comprised in
24 essentially the same manner as the transmitting antenna, and
25 is positioned in the tool in the same manner as the
26 transmitting antenna, so that the receiving antenna can
27 receive the electromagnetic energy which has traveled
28 through the material that is analyzed.

29
30 The present invention is especially useful in the field of
31 microwave diagnostics of fluid content and fluid quantity.
32 For example, the apparatus can couple electromagnetic energy
33 into mammal tissue. The electromagnetic energy can be
34 monitored to provide an indication of the amount and

01 distribution of a fluid, such as water, inside the mammal
02 tissue. One particularly useful application is to measure
03 the water content in a lung. The present apparatus is very
04 compact, and therefore requires a much smaller skin contact
05 area. Also, many antennas can be placed on a chest cavity,
06 to obtain a well defined image of the chest cavity. The
07 inventive antennas can be mathematically described as a
08 point source, thus making analysis of the data easier. A
09 conductive substance should be placed on the outside of the
10 chest cavity, to permit a sufficient flow of electromagnetic
11 energy into the chest cavity.

12
13 The prior art (Iskander et al.) has the drawback that the
14 electric field vanishes at some distance from the tool face,
15 since the fields in the two parallel slots are oppositely
16 directed. No such cancellation occurs with the present
17 invention. Furthermore, the incorporation of a resistor in
18 Iskander et al's antenna introduces a power limitation.

19
20 In another embodiment, the present invention can be used in
21 the field of microwave hyperthermia. The apparatus can
22 couple electromagnetic energy into the interior portion of a
23 mammal, so that the electromagnetic energy is focused to
24 heat and thereby reduce the size of or destroy a tumor.
25 Tumor reduction therapy or cancer therapy, by hyperthermia,
26 combined with radiation or drugs is known in the art to
27 either stop or slow down the growth of cancer cells, or
28 cause the death of the cancer cells.

29
30 The present invention has the advantage over the prior art
31 that many frequencies can be selected. Because there is no
32 limitation to the power handling capability in the inventive
33 antenna, the present invention is particularly suited for
34 depositing microwave power into a localized area inside a

01 mammal, such as a human. Either a single antenna or an
02 array of antennas could be used.

03

04 In yet another embodiment, the apparatus can be implanted
05 inside the body of a mammal, and used as a radio frequency
06 antenna. Either a single antenna or an array of antennas
07 could be used. As the inventive antenna can be made very
08 small (as small as approximately 10 mm long and
09 approximately 5 mm high), it is particularly suitable to
10 this application. As the antenna gets smaller, the
11 frequency coverage shifts to higher frequencies. The
12 apparatus can be constructed with a commercial micro-coaxial
13 connector. However, smaller devices can be constructed
14 through the use of a customized coaxial connector.

15

16 The apparatus can operate in the frequency domain, using a
17 single frequency, multiple frequencies (such as
18 simultaneous, selectable, or time-multiplexed for example),
19 or swept frequency techniques. Or, the apparatus can
20 operate in the time domain, using pulses of a wide variety
21 of shapes, widths, rise and fall times, etc. When the
22 pulses are transformed to the frequency domain, either
23 electronically using a spectrum analyzer, or numerically
24 using mathematical transforms, the same information is
25 obtained as would be given by a frequency domain tool.

26

27 A prototype tool was constructed, with the inventive
28 antennas. The tool consists of one transmitting and one
29 receiving antenna, the distance between them being variable.

30

31 An acceptable dielectric antenna must meet the following
32 criteria:

33

34

- 01 (i) It must be able to couple sufficient energy into
02 and from the material at its operating frequency
03 to allow probing of the material;
04
05 (ii) This probing energy must penetrate into the
06 material, rather than clinging to the surface of
07 the tool (i.e., it must travel as a freely
08 propagating wave rather than a surface wave guided
09 along the tool face).

10
11 In the present instance, the above two conditions must hold
12 over the entire range of the frequency of operation.

13
14 The first of the above criteria is tested by measuring the
15 return loss for the transmitting antenna, and the
16 transmission loss from the transmitting to the receiving
17 antenna - both as a function of frequency. These
18 measurements are shown in Figure 4 where the tool is placed
19 in air and against brine of conductivity 0.5 mho/m (to
20 represent a biological medium). The return loss curve in
21 brine shows that sufficient energy is entering the brine
22 over the frequency range of the measuring device
23 (Hewlett-Packard HP8505A Network Analyzer; 500 KHz -
24 1300 MHz) to permit probing. The transmission loss shows
25 that sufficient energy is being received at the receiving
26 antenna to permit measurements.

27
28 Measurements were made by using another measuring device
29 (HP3577A Network Analyzer; 5Hz - 200 MHz) to test the low
30 frequency limitation of the antenna. The results are shown
31 in Figure 5, showing that the low frequency limitation is
32 about 5 KHz. The improved return loss performance in the
33 200 MHz region (at Figure 4) results from a drying (curing)
34 of the epoxy alumina filling between measurements.

01 Figure 6 shows time-domain transmission measurements at
02 various distances (d) to a metal reflector plate in the
03 brine. The change in amplitude of the received pulse as a
04 function of the distance of the metallic reflector shows
05 that the energy has penetrated into the brine out to the
06 location of the plate.

07

08 While a preferred embodiment of the invention has been
09 described and illustrated, it should be apparent that many
10 modifications can be made thereto without departing from the
11 spirit or scope of the invention. Accordingly, the
12 invention is not limited by the foregoing description, but
13 is only limited by the scope of the claims appended hereto.

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CLAIMS:

1. Apparatus for coupling electromagnetic energy into materials comprising a measuring tool having a tool face, said measuring tool further comprising an electromagnetic transmitting antenna, said transmitting antenna further comprising:
 - (a) a coaxial cable connecting means and means to transmit electromagnetic energy therethrough;
 - (b) a stripline adapter capable of transmitting electromagnetic energy from said coaxial cable connecting means to a stripline having a metallic central strip, said center strip having a front end, a flat strip body, a flat strip face, and a distal end, said front end electrically connected to a center conductor of said stripline adapter, said strip face bent at approximately right angles to said strip body and having a height measured from said right angle bend to said distal end that is compatible with a desired frequency coverage;
 - (c) a ground plane which extends from said stripline adapter to said right angle bend, so that said distal end extends away from said ground plane and so that a void exists between said center strip and said ground plane;
 - (d) a dielectric largely filling said void, said dielectric comprised of a material having a very high dielectric constant and a very low energy loss, so that said transmitting antenna is positioned so that said ground plane is fixedly

01 connected to said measuring tool and said strip
02 face is positioned to lie flush with said tool
03 face so that said transmitting antenna can
04 transmit electromagnetic energy into said
05 material;

06

07 (e) an enclosure surrounding said stripline comprising
08 four metallic walls, said walls positioned in
09 electrical contact with said ground plane and said
10 stripline adapter, so that said strip face is
11 nearly centered in the opening created by said
12 walls and said ground plane;

13

14 (f) a loss-less, non-conducting material which fills
15 in any remaining open space in said enclosure so
16 that said non-conducting material forms an
17 additional wall that is nearly flat with said
18 strip face;

19

20 (g) said receiving electromagnetic antenna comprised
21 in essentially the same manner as said
22 transmitting antenna, said receiving antenna
23 positioned in said measuring tool in the same
24 manner as said transmitting antenna, so that said
25 receiving antenna can receive said electromagnetic
26 energy which has traveled through said material;
27 and

28

29 (h) means for monitoring the amplitude and the phase
30 of said received electromagnetic energy.

31

32 2. Apparatus as recited in Claim 1 further comprising a
33 means for positioning said tool face near said
34 material.

- 01 3. Apparatus as recited in Claim 1 wherein said
02 electromagnetic energy is focused to heat and thereby
03 reduce the size of a tumor in a mammal.
04
- 05 4. Apparatus as recited in Claim 1 wherein said
06 electromagnetic energy is focused to heat and thereby
07 destroy a tumor in a mammal.
08
- 09 5. Apparatus as recited in Claim 1 wherein said antennas
10 are positioned on a belt-mounted device.
11
- 12 6. Apparatus as recited in Claim 1, further comprising a
13 plurality of receiving antennas.
14
- 15 7. Apparatus as recited in Claim 6 further comprising a
16 plurality of transmitting antennas.
17
- 18 8. Apparatus as recited in Claim 7 wherein said materials
19 are mammal tissue and water.
20
- 21 9. Apparatus as recited in Claim 1, wherein broadband
22 measurements are taken to determine said dielectric
23 properties as a function of position within
24 said material.
25
- 26 10. An apparatus for coupling electromagnetic energy to
27 determine the quantity of a fluid in a material, said
28 apparatus having a tool face and further comprising a
29 first electromagnetic transmitting antenna, said first
30 transmitting antenna further comprising:
31
- 32 (a) a coaxial cable connecting means and means to
33 transmit electromagnetic energy therethrough;
34

- 01 (b) a stripline adapter capable of transmitting
02 electromagnetic energy from said coaxial cable
03 connecting means to a stripline having a metallic
04 central strip, said center strip having a front
05 end, a flat strip body, a flat strip face, and a
06 distal end, said front end electrically connected
07 to a center conductor of said stripline adapter,
08 said strip face bent at approximately right angles
09 to said strip body and having a height measured
10 from said right angle bend to said distal end that
11 is compatible with a desired frequency coverage;
12
13 (c) a ground plane which extends from said stripline
14 adapter to said right angle bend, so that said
15 distal end extends away from said ground plane and
16 so that a void exists between said center strip
17 and said ground plane;
18
19 (d) a dielectric filling most of said void, said
20 dielectric composed of a material having a very
21 high dielectric constant and a very low energy
22 loss, so that said first transmitting antenna is
23 positioned so that said ground plane is fixedly
24 connected to said logging tool and said strip face
25 is positioned to lie flush with said tool face so
26 that said first transmitting antenna can transmit
27 electromagnetic energy into said material;
28
29 (e) an enclosure surrounding said stripline comprising
30 four metallic walls, said walls positioned in
31 electrical contact with said ground plane and said
32 stripline adapter, so that said strip face is
33
34

01 nearly centered in the opening created by said
02 walls and said ground plane;

03
04 (f) a loss-less, non-conducting material which fills
05 in any remaining open space in said enclosure so
06 that said non-conducting material forms an
07 additional wall that is nearly flat with said
08 strip face;

09
10 (g) said receiving electromagnetic antenna comprised
11 in essentially the same manner as said
12 transmitting antenna, said receiving antenna
13 positioned in said apparatus in the same manner as
14 said transmitting antenna, so that said receiving
15 antenna can receive said electromagnetic energy
16 which has traveled through said material; and

17
18 (h) means for monitoring the amplitude and the phase
19 of said electromagnetic energy, so that the
20 quantity of said fluid can be determined.

21
22 11. Apparatus as recited in Claim 1 or 10 wherein said
23 transmitting antenna transmits and said receiving
24 antenna receives electromagnetic energy over a
25 frequency range of 2 KHz to 4 GHz.

26
27 12. Apparatus is recited in Claim 1 or 10 wherein said
28 transmitting antenna can alternately function as a
29 receiving antenna and said receiving antenna can
30 alternately function as a transmitting antenna.

31
32 13. Apparatus as recited in Claim 12 further comprising a
33 belt-mount, said belt-mount substantially conforming to
34

- 01 the outside of a mammal tissue and holding said
02 transmitting and receiving antennas.
03
- 04 14. Apparatus as recited in Claim 13 further comprising a
05 plurality of receiving antennas.
06
- 07 15. Apparatus as recited in Claim 14 further comprising a
08 plurality of transmitting antennas.
09
- 10 16. Apparatus as recited in Claim 10 wherein said fluids
11 are water.
12
- 13 17. Apparatus as recited in Claim 1 or 10 wherein said
14 ground plane is no greater than 10 mm in length.
15
- 16 18. Apparatus as recited in Claim 1 or 10 wherein said
17 strip face has a height that is no greater than 5 mm.
18
- 19 19. Apparatus as recited in Claim 1 or 10 wherein said
20 electromagnetic energy is monitored to provide an
21 indication of the amount and distribution of a fluid
22 inside mammal tissue.
23
- 24 20. Apparatus as recited in Claim 1 or 10 wherein no
25 receiving antenna is incorporated.
26
- 27 21. Apparatus as recited in Claim 1 or 10 wherein said
28 apparatus is implanted inside a mammal, as a radio
29 frequency antenna.
30
- 31 22. Apparatus as recited in Claim 21 wherein said apparatus
32 does not incorporate a receiving antenna.
33
34

- 01 23. Apparatus as recited in Claim 1 or 10 wherein a strip
02 transmission line is electrically connected to said
03 stripline, so that electromagnetic energy can be
04 transmitted thereto.
05
- 06 24. Apparatus as recited in Claim 10 wherein said nature of
07 said fluid is determined as a function of position in
08 said material.
09
- 10 25. Method for coupling electromagnetic energy into
11 materials comprising the steps of:
12
- 13 forming a measuring tool having a tool face, an
14 electromagnetic transmitting antenna and a receiving
15 antenna, said transmitting antenna further comprising:
16
- 17 (a) a coaxial cable connecting means and means to
18 transmit electromagnetic energy therethrough;
19
- 20 (b) a stripline adapter capable of transmitting
21 electromagnetic energy from said coaxial cable
22 connecting means to a stripline having a metallic
23 central strip, said center strip having a front
24 end, a flat strip body, a flat strip face, and a
25 distal end, said front end electrically connected
26 to a center conductor of said stripline adapter,
27 said strip face bent at approximately right angles
28 to said strip body and having a height measured
29 from said right angle bend to said distal end that
30 is compatible with a desired frequency coverage;
31
- 32 (c) a ground plane which extends from said stripline
33 adapter to said right angle bend, so that said
34 distal end extends away from said ground plane and

01 so that a void exists between said center strip
02 and said ground plane;

03

04 (d) a dielectric largely filling said void, said
05 dielectric comprised of a material having a very
06 high dielectric constant and a very low energy
07 loss, so that said transmitting antenna is
08 positioned so that said ground plane is fixedly
09 connected to said measuring tool and said strip
10 face is positioned to lie flush with said tool
11 face so that said transmitting antenna can
12 transmit electromagnetic energy into said
13 material;

14

15 (e) an enclosure surrounding said stripline comprising
16 four metallic walls, said walls positioned in
17 electrical contact with said ground plane and said
18 stripline adapter, so that said strip face is
19 nearly centered in the opening created by said
20 walls and said ground plane;

21

22 (f) a loss-less, non-conducting material which fills
23 in any remaining open space in said enclosure so
24 that said non-conducting material forms an
25 additional wall that is nearly flat with said
26 strip face;

27

28 (g) said receiving antenna comprised in essentially
29 the same manner as said transmitting antenna, and
30 positioned in said measuring tool in the same
31 manner as said transmitting antenna, so that said
32 receiving antenna receives said electromagnetic
33 energy which has traveled through said material;

34

01 interconnecting said measuring tool with a means for
02 monitoring said electromagnetic energy whereby said
03 dielectric properties can be measured; and
04
05 interconnecting said measuring tool with a source of
06 electromagnetic energy.
07
08 26. Method as recited in Claim 25 further comprising a
09 means for positioning said tool face near said
10 material.
11
12 27. Method as recited in Claim 25 wherein said
13 electromagnetic energy is focused to heat and thereby
14 reduce the size of a tumor in a mammal.
15
16 28. Method as recited in Claim 25 wherein said
17 electromagnetic energy is focused to heat and thereby
18 destroy a tumor in a mammal.
19
20 29. Method as recited in Claim 25 wherein said antennas are
21 positioned on a belt-mount device.
22
23 30. Method as recited in Claim 25 further comprising a
24 plurality of receiving antennas.
25
26 31. Method as recited in Claim 30 further comprising a
27 plurality of transmitting antennas.
28
29 32. Method as recited in Claim 31 wherein said materials
30 having dissimilar dielectric properties are
31 mammal tissue and water.
32
33 33. Method as recited in Claim 25 wherein said broadband
34 measurements are taken to determine said dielectric

01 properties as a function of position within
02 said material.

03

04 34. Method for coupling electromagnetic energy to determine
05 the quality of a fluid in a material, comprising the
06 steps of:

07

08 forming an apparatus having a tool face, an
09 electromagnetic transmitting antenna, and a receiving
10 antenna, said transmitting antenna further comprising:

11

12 (a) a coaxial cable connecting means and means to
13 transmit electromagnetic energy therethrough;

14

15 (b) a stripline adapter capable of transmitting
16 electromagnetic energy from said coaxial cable
17 connecting means to a stripline having a metallic
18 central strip, said center strip having a front
19 end, a flat strip body, a flat strip face, and a
20 distal end, said front end electrically connected
21 to a center conductor of said stripline adapter,
22 said strip face bent at approximately right angles
23 to said strip body and having a height measured
24 from said right angle bend to said distal end that
25 is compatible with a desired frequency coverage;

26

27 (c) a ground plane which extends from said stripline
28 adapter to said right angle bend, so that said
29 distal end extends away from said ground plane and
30 so that a void exists between said center strip
31 and said ground plane;

32

33 (d) a dielectric largely filling said void, said
34 dielectric comprised of a material having a very

01 high dielectric constant and a very low energy
02 loss, so that said transmitting antenna is
03 positioned so that said ground plane is fixedly
04 connected to said measuring tool and said strip
05 face is positioned to lie flush with said tool
06 face so that said transmitting antenna can
07 transmit electromagnetic energy into said
08 material;

09
10 (e) an enclosure surrounding said stripline comprising
11 four metallic walls, said walls positioned in
12 electrical contact with said ground plane and said
13 stripline adapter, so that said strip face is
14 nearly centered in the opening created by said
15 walls and said ground plane;

16
17 (f) a loss-less, non-conducting material which fills
18 in any remaining open space in said enclosure so
19 that said non-conducting material forms an
20 additional wall that is nearly flat with said
21 strip face;

22
23 (g) said receiving antenna comprised in essentially
24 the same manner as said transmitting antenna, and
25 positioned in said apparatus in the same manner as
26 said transmitting antenna, so that said receiving
27 antenna receives said electromagnetic energy which
28 has traveled through said material;

29
30 interconnecting said measuring tool with a means for
31 monitoring said electromagnetic energy whereby said
32 nature of said fluid can be determined; and
33
34

- 01 interconnecting said apparatus with a source of
02 electromagnetic energy.
03
- 04 35. Method as recited in Claim 31 or 40 wherein said
05 transmitting antenna transmits and said receiving
06 antenna receives electromagnetic energy over a
07 frequency range of 2 KHz to 4 GHz.
08
- 09 36. Method as recited in Claim 25 or 34 wherein said
10 transmitting antenna can alternately function as a
11 receiving antenna and said receiving antenna can
12 alternately function as a transmitting antenna.
13
- 14 37. Method as recited in Claim 36 further comprising a
15 belt-mount, said belt-mount substantially conforming to
16 the outside of a mammal tissue and holding said
17 transmitting and receiving antennas.
18
- 19 38. Method as recited in Claim 37 further comprising a
20 plurality of receiving antennas.
21
- 22 39. Method as recited in Claim 38 further comprising a
23 plurality of transmitting antennas.
24
- 25 40. Method as recited in Claim 39 wherein some of said
26 antennas are positioned on said tool face and some
27 antennas are positioned on said belt-mount.
28
- 29 41. Method as recited in Claim 34 wherein said fluids are
30 water.
31
- 32 42. Method as recited in Claim 25 or 34 wherein said ground
33 plane is no greater than 10 mm in length.
34

- 01 43. Method as recited in Claim 25 or 34 wherein said strip
02 face has a height that is no greater than 5 mm.
03
- 04 44. Method as recited in Claim 25 or 34 wherein said
05 electromagnetic energy is monitored to provide an
06 indication of the amount and distribution of a fluid
07 inside mammal tissue.
08
- 09 45. Method as recited in Claim 25 or 34 wherein no
10 receiving antenna is incorporated.
11
- 12 46. Method as recited in Claim 25 or 34 wherein said
13 apparatus is implanted inside a mammal, as a radio
14 frequency antenna.
15
- 16 47. Method as recited in Claim 46 wherein said apparatus
17 does not incorporate a receiving antenna.
18
- 19 48. Method as recited in Claim 25 or 34 wherein a strip
20 transmission line is electrically connected to said
21 stripline, so that electromagnetic energy can be
22 transmitted thereto.
23
- 24 49. Method as recited in Claim 40 wherein said quantity of
25 said fluid is determined as a function of position
26 within said material.
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Patents Act 1977
Examiner's report to the Comptroller under
Section 17 (The Search Report)

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(i) UK Cl (Edition K) G1N (NCLA, NCLE, NCLL, NENX)

(ii) Int Cl (Edition 5) A61B, A61N, G01V

Search Examiner

D J MOBBS

Databases (see over)

(i) UK Patent Office

(ii)

Date of Search

28 FEBRUARY 1992

Documents considered relevant following a search in respect of claims

1-49

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
A	US 4678997 (JANES)	

SF2(p)

1me - c:\wp51\doc99\fil000442

51

Category	Identity of document and relevant passages	Relevant to claim(s)

Categories of documents

X: Document indicating lack of novelty or of inventive step.

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